PROTOCOLS FOR THERMAL AND EMISSIONS PERFORMANCE TESTING OF DOMESTIC FUELS AND STOVES

Tafadzwa Makonese

Student Number: 200946372

Department of Geography, Environmental Management and Energy Studies

Supervisor: Professor H. J. Annegarn

Co-supervisor: James W. Robinson, SeTAR Centre

Department of Geography, Environmental Management and Energy Studies

University of Johannesburg

A thesis submitted in partial fulfilment of the requirements for the degree MPhil (Energy Studies) in the Faculty of Science at the University of Johannesburg

27 June 2011

Affidavit

To whom it may concern

This serves to confirm that I, Tafadzwa Makonese, Passport Number AN804569, Student number 200946372, enrolled for the qualification MPhil (Energy Studies) in the Faculty of Science, herewith declare that my academic work is in line with the Plagiarism Policy of the University of Johannesburg, with which I am familiar.

I further declare that the work presented in the thesis**:**

Protocols for Thermal and Emissions Performance Testing of Domestic Fuels and Stoves

is authentic and original unless clearly indicated otherwise, and in such instances full reference to the source is acknowledged, and I do not pretend to receive any credit for such acknowledged quotations, and that there is no copyright infringement in my work. I declare that no unethical research practices were used or material gained through dishonesty. I understand that plagiarism is a serious offence and that, should I contravene the Plagiarism Policy notwithstanding signing this affidavit, I may be found guilty of a serious criminal offence (perjury) that would amongst other consequences compel the UJ to inform all other tertiary institutions of the offence and to issue a corresponding certificate of reprehensible academic conduct to whomever request such a certificate from the institution.

Signed at Johannesburg on this _______ day of _______________ 2011

____

Tafadzwa Makonese

STAMP COMMISSIONER OF OATHS
Affidavit certified by a Commissioner of Oaths
This affidavit conforms with the requirements of the JUSTICES OF THE PEACE AND COMMISSIONERS OF OATHS ACT 16 OF 1963 and the applicable Regulations published in the GG GNR 1258 of 21 July 1972; GN 903 of 10 July 1998; GN 109 of 2 February 2001 as mended.

Declaration

The work contained in this thesis is my own, unless otherwise acknowledged. This thesis has not been presented for examination at any other university.

Parts of this thesis have been presented and published previously at various national and international conferences, as listed below:

Kimemia, D. K., **T. Makonese**, T. V. Molapo, H. J. Annegarn (2009): Biomass alternative urban energy economy: case of Setswetla, Alexandra Township, Gauteng, *NACA Annual Conference*, Vereeniging, 14-16 October 2009. A poster was presented.

Tafadzwa Makonese assisted **20%** in the design of the poster and David Kimemia presented the poster. Prof Annegarn co-authored and edited the poster. Portions from the poster appear in chapter 3 of the thesis.

Molapo, T. V**,** C. Pemberton-Pigott, H. J. Annegarn, D. Milosavljevic, D. K. Kimemia, **T. Makonese** (2009), Comparison of emissions from top lit up-draft (TLUD) and bottom lit up-draft (BLUD) *imbaulas***,** *NACA Annual Conference*, Vereeniging, 14-16 October 2009. A poster was presented.

Tafadzwa Makonese assisted **10%** in the design of the poster and Vincent Molapo presented the poster. Prof Annegarn co-authored and edited the poster. Portions from the poster appear in the thesis in chapter 3 and 4.

Robinson, J., **T. Makonese**, C. Pemberton-Pigott, H. J. Annegarn (2010), Heterogeneous Stove Testing Protocols for Emissions and Thermal Performance, *Domestic Use of Energy Conference*, Cape Peninsula University, Cape Town, 29-31 March, 2010. Contribution appeared in the proceedings as full paper (Peer Reviewed).

James Robinson authored the paper and presented it. **Tafadzwa Makonese** co-authored **20%** of the paper. Prof Annegarn co-authored and edited the paper. Portions from the paper appear in the thesis in chapter 3 and 4.

Kimemia, K. D., **T. Makonese**, J. Robinson, T. V. Molapo, H. J. Annegarn (2010), Characterisation of Domestic Biomass Combustion Technologies used in Setswetla, Alexandra Township, Gauteng, *Domestic Use of Energy Conference*, Cape Peninsula University, Cape Town, 29-31 March, 2010. Contribution appeared in the proceedings as full paper (Peer Reviewed).

David Kimemia authored paper and presented it at the conference. **Tafadzwa Makonese** co-authored **20%** of the paper. Prof Annegarn co-authored and edited the paper. Portions from the paper appear in chapter 3 of the thesis.

Makonese, T., J. Robinson, C. Pemberton-Pigott, H. J. Annegarn (2010), A heterogeneous testing protocol for certifying stove thermal and emissions performance for GHG and air quality management accounting purposes, *Air and Water Management Association's Specialty Conference*, Grand Park Hotel, Xi'an, China, 10-14 May 2010. Contribution appeared in the proceedings as an abstract.

Tafadzwa Makonese authored **60%** of the paper with the assistance of the co-authors and presented it at the conference. Prof Annegarn co-authored and edited the paper. Portions from the paper appear in chapter 3 and 4 of the thesis.

Makonese, T., J. Robinson, C. Pemberton-Pigott, H. J. Annegarn (2010), South African paraffin stoves: A comparative analysis of thermal and emissions performance, *National Association of Clean Air (NACA)*, Protea Hotel, Polokwane, 13-15 October 2010. Contribution appeared in the proceedings as an abstract.

Tafadzwa Makonese authored **70 %** of the paper with the assistance of the co-authors and presented it at the conference. Prof Annegarn co-authored and edited the paper. Portions from the paper appear in chapter 3 and 4 of the thesis.

Makonese, T., J. Robinson, D. K. Kimemia, T. V. Molapo, H. J. Annegarn (2010), Domestic combustion of solid fuels: The need for heterogeneous testing protocols for thermal and emissions performance, *People's Energy Network (PEN) Conference*, University of Botswana, Gaborone, Botswana, 20-22 October 2010.

Tafadzwa Makonese authored **60%** of the paper with the assistance of the co-authors and presented it at the conference. Prof Annegarn co-authored and edited the paper. Portions from the paper appear in chapter 2, 3 and 4 of the thesis.

Makonese, T., J. Robinson, C. Pemberton-Pigott, T. V. Molapo, H. J. Annegarn (2010), A heterogeneous testing protocol for certifying stove thermal and emissions performance for GHG and air quality management accounting purposes, *Air and Water Management Association* (*AWMA*) Conference, Xian, China, 10-14 May 2010. Contribution appeared in the proceedings as an extended abstract (Peer Reviewed)

Tafadzwa Makonese authored **50%** of the paper assisted by co-authors. Prof Annegarn co-authored and edited the paper. Portions from this paper appear in all chapters of the thesis.

Makonese, T., J. Robinson, C. Pemberton-Pigott, H. J. Annegarn (2011), A preliminary comparison of stove testing methods between the Water Boiling Test and the *heterogeneous* testing protocol, *Domestic Use of Energy Conference*, Cape Peninsula University of Technology, Cape Town, 11-13 April 2011. Paper appears in conference proceedings.

Tafadzwa Makonese authored **60%** of the paper with the assistance of the co-authors and was presented at the conference. Prof Annegarn co-authored and edited the paper. Portions of the paper appear in chapter 2, 3 and 4 of the thesis.

Dedication

This work is dedicated to Gertrude Mafusire-Makonese

and Panashe Phil Jnr. Makonese.

Acknowledgments

I am indebted to several individuals, groups and organisations for making this study a success. First and foremost, I would like to express my sincere gratitude to my supervisor and mentor, Professor Harold John Annegarn. I thank him for his patience, guidance, support and council throughout the duration of the study. I am grateful to him for organising and providing the necessary equipment for the smooth running of the study. Importantly, I am indebted to him for exposing me to the academic science and stove community, and for providing me with the much needed financial support. Prof Annegarn, thank you for giving me the opportunity and the confidence to soar like an eagle. Thank you for instilling in me self-belief. Here is hoping that you are proud of your faithful investments in me.

I would also like to thank James William Robinson for his co-supervision since the inception of this project. I further thank Crispin Pemberton-Pigott for sparing his valuable time in analysing my experimental data and results. He continually reviewed the spreadsheet to meet demands for quality. His expertise in the stove designing/testing field was a pillar in the development and progress of this thesis. Chris Bradnum, HOD of Faculty of Arts and Design Architecture (FADA), thank you for assisting me with the technical description and operational behaviours of different paraffin stoves. To Dr. Godfrey Chikowore and David Kimemia, thank you for taking time off your busy schedules to edit and review my work.

I am indebted to my colleagues and graduate students in the department of Geography, Environmental Management and Energy Studies, and those based at the Sustainable Energy Technologies and Research (SeTAR) Centre. Thank you to Vincent Molapo and David Kimemia for assisting with the stove tests and for encouraging me to remain steadfast in this never ending journey.

Special thank you goes to Beverley Terry for organising our conference trips and accommodation, and her constant nagging for perfection and high achievements. Bev, you will always be a star. Maud Khumalo, thank you for your support and encouragements when the chips were down.

I wish to acknowledge GIZ, formally GTZ/ProBEC for funding the SeTAR stove testing laboratory where the experimental work of this thesis was carried out.

Lastly, thank you to the following institutions for financial support: Central Energy Fund (CEF) through GTZ/ProBEC; South Africa National Energy Research Institute (SANERI); the National Research Foundation through grant-holder bursary through the Focus Area Grant *Energy as a Key Technology for a Sustainable Megacity City – Gauteng* (No. FA2006022800010) to H. J. Annegarn.

Abstract

The combustion of fuels in poorly designed cookstoves is a major anthropogenic source of atmospheric emissions with severe environmental and health implications. It is widely acknowledged that these challenges are best addressed with the development and dissemination of clean cookstoves. Widely used stove testing protocols (UCB *Water Boiling Test* and variants) are often single task-based and not representative of real-world uses or likely combinations of the manner in which fuels, stoves and pots may be used. The hypothesis of this study is that *a stove testing procedure that provides for testing of stove/fuel/pot combinations, in a sequence of heterogeneous tests, provides a better representation of thermal performance and emissions than existing protocols based on prescribed fuels and fuel loads, and single tasks.* The study aimed to develop and evaluate a set of testing protocols for determining thermal efficiency and emissions performance of domestic fuels and cooking devices to satisfy the rigorous performance specifications expected for claims under the Clean Development Mechanism (CDM) carbon trading market.

The *Heterogeneous stove Testing Protocol* (HTP) was developed and documented as a complete set of *standard operating procedures* (SOPs), using a template derived from the Desert Research Institute (DRI), Reno, Nevada, and used for performance evaluation of fuel/stove combinations. The effect of pot size on the performance of two paraffin wick stoves and a pressurised paraffin stove was assessed and was found not to be a major factor, which affected thermal efficiency only at the *high* power setting. Power setting was found to influence the thermal efficiency and combustion performance of all stoves tested, indicating the need for assessment of the devices across the full range of power settings (where feasible). The *HTP* was also employed in characterising the combustion performance of coal stoves, using three different ignition methods, giving qualitative and quantitative results. Compared to the *bottom-lit up-draft* (BLUD) ignition method, the *Basa njengo Magogo,* also referred to as the *top-lit up draft* (TLUD) method, proved to be a better method of coal fires ignition, in terms of reduced $CO:CO_2$ ratio and less smoke generation than in conventional braziers. The *bottom-lit down-draft* (BLDD) ignition method, incorporated in the SeTAR prototype coal stove, was found to be effective in fuel utilisation and improved combustion efficiency compared to the TLUD and BLUD methods, with $CO:CO_2$ emission factors below 1% for 230 minutes.

A number of parameters employed by the Water Boiling Test (WBT) were examined and compared with the *HTP* (e.g. turn-down ratio; simmer process; hot-start phase; use of standardised fuels and test pots). The *HTP* was found to provide more representative performance data over a wide range of use scenarios, the equivalent of providing performance curves rather than the minimum and maximum performance points provided by the WBT. The findings of this study have shown that the *Heterogeneous stove Testing Protocol* is consistent, robust, and transportable; making it a valuable tool for stove design improvements, and for the assessment of stoves under voluntary and compulsory carbon markets.

Table of Contents

List of Figures

List of Tables

Glossary of Terms

This section defines terms as they are used in this thesis. In other contexts the same terms can be used to define different parameters, some of which are discussed in the body of the text.

Ash: "*The solid residue of combustion. The chemical composition of an ash depends on the substance burned. Wood ash contains metal carbonates (e.g., potassium carbonate) and oxides formed from metals originally compounded in the wood.*"
www.greenwoodtechnologies.com/glossary.htm

***Bottom-lit up-draft* (BLUD):** In the BLUD fire lighting method, the fuel is ignited from the bottom and the method relies on the upward movement of draft to keep the flame alive. The hot zone starts at the bottom, but then the hot pyrolysis front migrates upward until reaching the top of the fuel pile. The order of laying the fire proceeding is as follows: paper, wood, ignition, after which coal is added at an appropriate time after the wood fire is established.

***Bottom-lit down-draft* (BLDD):** The BLDD ignition method entails lighting the fuel from the bottom and the method relies on the downward movement of drafts to keep the flame alive. The flame is projected *downward* by a draft induced by the chimney, while there is an upward migration of the pyrolytic zone through the bed of coal.

***Basa njengo Magogo* (*BnM*):** The *BnM* ignition method is an alternative way of lighting a fire in an *imbaula* stove. The order of laying the fire is: coal, paper, and then wood, with a few lumps of coal added at an appropriate time after the fire has been lit. For the conventional method, this order is reversed.

Burn rate (r): Rate of fuel mass loss during combustion [g minute^{-1}].

Combustion efficiency: An indicator of the completeness of the conversion of fuel carbon into carbon dioxide, expressed as the CO:CO_2 ratio. "*Combustion efficiency relates to the amount of the energy from the biomass that is converted into heat energy.*" [%]. www.pciaonline.org

Conduction: "*...heat transfer across a surface, or transfer of heat through a material by passing from one molecule to another.*" Conduction is one of the three forms of heat transfer. www.greenwoodtechnologies.com/glossary.htm

Convection: "*The transfer of heat that occurs due to the circulation of air*" or liquid. Convection is one of the three forms of heat transfer. www.greenwoodtechnologies.com/glossary.htm

Draft: "*The movement of air through a stove and up a chimney.*" www.pciaonline.org

Emissions: "*The byproducts from the combustion process that are discharged into the air*". www.pciaonline.org

Excess air: "*The amount of air used in excess of the amount for complete (stoichiometric) combustion of the fuel*." [%]. www.pciaonline.org

Fire-power (P): Average rate of heat release by the fuel combustion over the entire task [kilowatts].

Flue gas: "*The hot gases that flow from the combustion chamber and out the chimney (if the chimney is present)*." www.johnosoriobuck.com

Grate: "*A framework of bars or mesh used to hold fuel in a stove*." www.johnosoriobuck.com

Greenhouse gas (GHG): "*A greenhouse gas is a gas that absorbs and emits radiation within the thermal infrared range. The primary greenhouse gases in the Earth's atmosphere are water vapour, carbon dioxide, methane, nitrous oxide and ozone*." www.ecofast-africa.com/environment/

***Heterogeneous stove Testing Protocol* (HTP):** The *HTP* is a protocol to assess the performance of a stove across a range of conditions, using stove conditions, fuels and pot sizes for which the stove was designed. It requires that thermal and emissions performance tests be carried out using two pot sizes over the full range of a stove's adjustable power settings.

Lower heating value (LHV): - refers to the "*…theoretical maximum amount of energy that can be extracted from the combustion of the moisture-free fuel if it is completely combusted and the combustion products are cooled to room temperature but the water produced by the reaction of the fuel bound hydrogen remains in the gas phase*" (Bailis *et al*., 2007b:21).

Heat transfer efficiency: "*The percentage of heat released from combustion which enters a pot*." [%]. www.pciaonline.org

High power: "*A mode of stove operation where the objective is to boil water as quickly as possible; the highest power at which a stove can operate*." [Kilowatts]. www.pciaonline.org

Low power: "*A mode of stove operation where the objective is to simmer the water/food product or warm the food; the lowest power setting at which a stove can operate and still maintain a flame and simmer food.*" [Kilowatts]. www.pciaonline.org.

Medium power: "*A mode of stove operation where the objective is to simmer the water or food product; the mid-range power*" (mid-range between low and high power) at which a stove can operate. [Kilowatts]. www.pciaonline.org

Pyrolysis: The destructive distillation of a hydrocarbon fuel in the absence of oxygen, yielding a mixture of gaseous components and a solid char residue.

Radiation: The transfer of heat by emission and absorption of electromagnetic radiation, in this context in the thermal infrared and visible wavebands. Radiation is one of the three forms of heat transfer.

Standard operating procedure (SOP): "*A set of fixed instructions or steps for carrying out routine analytical or testing operations*." www.ask.com/dictionary

Smoke: A dense, visible aerosol**,** comprising a mixture of solid or liquid particles in a gas stream derived from the combustion of a fuel. Smoke is often an indicator incomplete combustion.

Specific fuel consumption: Fuel consumption per liter of water boiled or Kg of food cooked, averaged over the completion of a specific task, such as bringing to the boil 5 L or 2 L of water.

Thermal Efficiency (ŋ): The ratio of energy retained by water (in the pot) to the energy released by the fuel combustion. The energy absorbed by the pot itself is not regarded as part of the function. [%].

Time to boil: Average time (minutes) taken for a specified volume of water to be heated from ambient temperature to the boil during the *high* power tests.

Top-lit up-draft **(TLUD):** The TLUD ignition method entails that the fuel is ignited from the top and the upward movement of drafts through the stove keeps the flame alive. The hot zone starts at the top, but then the hot pyrolysis front migrates downward until reaching the bottom of the fuel pile. The order of laying a fire is as follows: fuel, paper, and wood, with little fuel added at an appropriate time after the fire has been lit. The *Basa njengo Magogo* ignition is an example of a TLUD method of lighting a fire.

Turn-down ratio (TDR): fire-power of the stove at its *high* power setting over the fire-power of the stove at its *low* power setting, as defined for the HTP. Calculation of **TDR** is defined differently in **WBT** and ***HTP***

Water Boiling Test (WBT): The "*Water Boiling Test is a rough simulation of the cooking process that is intended to help stove designers understand how well energy is transferred from the fuel to the cooking pot*." It is divided into three phases: a high power cold start, a hot start, and a simmer test. (Bailis *et al*., 2007b:1).

CHAPTER ONE

This chapter introduces fuel/stove use in developing countries in Africa and domestic stove testing programmes in general. A problem statement is formulated, the domain of the study specified, aim and objectives set out. A justification of the study is presented and the general approach to the study is outlined.

1. Domestic Fuel Use in Developing Countries

"*Combustion of fuelwood, charcoal and* petroleum products *is a daily practice* for domestic purposes for *about half of the world's population*" (Ludwig *et al.,* 2003:23) and about 80% of people in the Southern African Development Community (SADC). Of the estimated one-third of Africa's population who live in urban areas, only about 25% have access to electricity (Karekezi & Majoro, 2002). Winkler *et al*. (2006:34) reported that "…*electricity provided 62% of the total energy consumed by South African households in 2005." "Biomass (14%), coal (8%), paraffin*[1] *(12%), vegetable wastes (6.9%), liquefied petroleum gas (LPG) (2%) and use of candles (2%)"* provided the balance of the household energy consumed. The patterns of household fuel use are heterogeneous, as are the people, the environment and the cultures that depend on these fuels to meet their essential cooking needs (Masera *et al.,* 2005). The combustion of these fuels is a major anthropogenic source of atmospheric emissions. The resulting pollutants include: particles (condensed hydrocarbons droplets, soot, fly ash and other aerosol particles), sulphur gases (H_2S and SO_2), nitrogen oxides (NO_x), carbon monoxide (CO) and carbon dioxide (CO_2) (Barnes *et al*., 2009).

"*A significant fraction of all domestic combustion processes occurs in enclosed or semi enclosed small combustion devices*" (Zhang *et al*., 2000:4537) including metal braziers, ceramic and steel stoves. The cumulative emissions from multiple devices contribute to local and global air quality problems. This has been argued in several reviews, for example: "*Although household stoves are individually small, their use in numerous households has the potential to contribute significantly to inventories of greenhouse gases (GHG) especially in developing countries.*" (Zhang *et al.,* 2000:4538). Mitra *et al*. (2002:903) argue that "…*emissions from combustion of biomass and fossil fuels result in the generation of a large number of particle and gaseous products in ambient and indoor air, which create health and environmental risks*". Thus a number of stove improvement programmes have been implemented in different communities and countries to address the above

[1] 'Paraffin' is a term predominantly used in the southern parts of Africa and it is also known as 'kerosene' elsewhere especially in Northern Africa, the USA, Australia and New Zealand

concerns. Such programmes have been supported by respective governments, organisations, scientific institutions and funding agencies, aimed at reducing the emission of particulate matter and gases into the atmosphere (Madubansi & Shackleton 2007; WHO, 2002a).

"*In South Africa, urbanisation and the rapid growth of informal settlements have exacerbated the backlog in the provision of basic services such as electricity and waste removal*" (Scorgie *et al.,* 2005:4). The decision by the National Energy Regulator of South Africa (NERSA) on 25 June 2009 to allow Eskom to factor in an average price increase of 31.3% on electricity tariffs (National Treasury, 2009) has contributed to the continued use, of biomass fuels, coal, and paraffin in low-income domestic settings; even in electrified households.

The cost-effectiveness of biomass, coal, charcoal and paraffin for both cooking and space heating, relative to electricity or LPG, and the multifunctional nature of combustion devices, are major factors inhibiting the transfer to the supposedly higher forms of energy (*moving up the energy ladder*) (Barnes *et al*., 2005; Barnes & Floor, 1999). Furthermore, "…*humanity's ascent of the energy ladder is not guaranteed and if alternatives are neither available nor affordable, households and communities can also descend the energy ladder to lower quality forms of biomass, including animal dung and crop residue*." (Venema & Rehman 2007:888). "*Foley (1995) suggests using an energy demand ladder rather than fuel preferences ladder in that as incomes grow, people tend to demand more diversified energy sources to meet their energy requirements since they can afford to buy a variety of appliances, each of which requires a specific fuel source* (Heltberg, 2005:341). The use of multiple fuels has been termed *fuel stacking* for a given purpose (Davis, 1998; Masera *et al.,* 2000).

1.1 Domestic Air Pollution Issues in South Africa

In South Africa, air quality degradation from human settlements is associated primarily with the use of coal as a domestic energy source in the low income townships (Annegarn, 2006; Annegarn & Sithole, 1999). "*In these areas, both industry and households are responsible for emissions that may be locally severe.*" (Standish *et al.,* 2007:27). "*Despite widespread electrification, over half of South African households are still primarily dependent on solid fuels (coal, charcoal and wood*)" (Barnes *et al*., 2004:543) and liquid fuels (paraffin, gel fuels) for cooking and space heating (Madubansi & Shackleton, 2006; Howells *et al.,* 2005; Statistics South Africa, 2003). "*This results in levels of indoor air quality that often exceeds international air quality standards*." (Barnes *et al*., 2004:543). High levels of indoor air pollution in some areas and communities are associated with high levels of poverty and marginalisation (Scorgie *et al.,* 2005).

Paraffin use in the informal settlements of South Africa has proven to be catastrophic on both health and safety accounts. There have been high numbers of domestic paraffin-related accidents, which range from paraffin poisoning, to burns and destruction of houses and property by fire. "…w*hile shack-fires are common every day occurrences in the informal settlements and shanty towns that ring the Greater Johannesburg metropolitan region, most go largely unnoticed and unrecorded, and hence are excluded from public consciousness.*" (Murray, 2009:167). The annual externality cost of paraffin use in South Africa is estimated to be fifty times higher than the annual turn over value (PDC, 2004). Faulty and sub-standard paraffin appliances are believed to be a major cause of uncontrolled fires in low income households and informal settlements (Truran, 2009).

Recent trends emphasise the identification of cost effective emission reduction opportunities aimed at reducing health impacts of indoor air pollution resulting from unvented stoves (WHO, 2002a). "*In an attempt to address some of the issues of traditional stoves, governments, humanitarian organisations, and corporations have introduced a great variety of stove designs to many areas of the developing world*" (Taylor, 2009:2). Sasol Infrachem (Sasolburg) and the NOVA Institute have supported projects in South Africa on smoke reduction from domestic coal fires, such as the dissemination of the *Basa njengo Magogo* (*BnM*) approach. This *BnM* approach is a simple intervention in the way domestic fires are lit, involving a top-down approach to fuel loading and ignition in *imbaulas*[2] and stoves (Wagner *et al.,* 2005), and has become a national priority energy intervention programme[3]. The Department of Minerals and Energy (DME) formulated an *Integrated Household Clean Energy Strategy* (IHCES) with emphasis on the *BnM* intervention in the short-to-medium term (DME, 2004). This method is estimated to result in at least an 80% reduction in ambient particulate air pollution and a 20% reduction in coal use at no additional cost to the household (Le Roux *et al.*, 2009).

1.2 Stoves, Stove Emissions and Stove Testing

Improved cookstoves are beginning to address a comprehensive set of issues ranging from local health (Barnes *et al*., 2009; Bruce *et al*., 2000) and environmental implications to global impacts associated with greenhouse gas (GHG) emissions (Solomon *et al*., 2009). Experience from past stove programme failures has shown that a successful cookstove program is more than just building or disseminating novel design cookstoves. "*The whole 'cooking system' needs to be considered through integrated approaches that work simultaneously with technology innovation, creative financing and market development, and the monitoring of actual health and environmental benefits.*

[2] Adapted from the word 'barrel' also variously spelled: *mbawula, embaula, embawula, imbawula, and imbaula*. Several new commercial products bearing no resemblance to it also use or have registered the word as their product name.

[3] Opening address by the Minister of Energy, Ms. D. E. Peters at the SAEEC Conference at Emperors Palace in Johannesburg on 13 November 2009.

The programs also foster participatory approaches that seek the involvement of local women to correctly address users' priorities and preferences." (Masera *et al.,* 2005:25).

In South Africa, several readily available stoves on the market do not have satisfactory performance in terms of emissions and thermal performance. Selected studies have indicated that such stoves have basic and unsafe designs that burn fuel poorly and emit harmful gases and particulate matter into the atmosphere (Makonese *et al.,* 2010a; Truran, 2009; Lloyd, 2002). These stoves are aggravating the problem which they are intended to alleviate - that of indoor pollution - partly because the new stoves are not properly tested against known baseline criteria (Taylor, 2009).

1.2.1 Stove testing

There is a growing interest for specifying performance of stoves powered by solid and liquid fuels, driven in large measure by need for certification of emission reductions under the Kyoto Protocol and Millennium Development Goals. Several of the more widely used protocols for solid fuel stoves (wood, charcoal, coal) are prescriptive in the type of fuel used, in an effort to derive a standardised test. However, the introduction of standardised fuels imposes conditions that are often not representative of real-world uses or likely combinations of the manner in which fuels, stoves and pots may be used. Therefore, there is an urgent need for robust testing protocols that allow for representative and reproducible testing and inter-comparison of the thermal performance and emissions from a diverse range of fuel/stove/pot combinations (Robinson *et al.,* 2010). Such a protocol should provide for the tested combination to be representative of either the stove design parameters or of typical uses.

Although there have been stove testing and dissemination campaigns aimed at reducing greenhouse gases and indoor pollution, many of these campaigns have failed due to the stoves not performing to user expectations. This is partly because emphasis had not been placed on the fuel/stove/pot/user nexus during the testing procedure. Stove types tested should be "…*those most typical for burning each type of fuel*." (Edwards *et al.,* 2003:203). According to Annegarn *et al*. (2009) the stove must be optimised with probable fuels, pots and lids for which they were designed. Ballard-Tremeer (1997) reported that the stove programmes were a failure because of the inability to simulate cooking procedures and user behaviour during the stove testing process. During the testing procedures erroneous assumptions were made about the optimisation of the stove. For example, previous studies on stove programmes made assumptions that improving efficiency leads to a reduction in emissions (Karekezi, 1992; Bialy, 1991; Baldwin, 1987). It has been shown by Smith (1992) and Ahuja *et al*. (1987) that "…*heat transfer can be improved while at the same time compromising the combustion efficiency*" (Ballard-Tremeer, 1997:4). Depending on the fuel/stove combination, this often gives rise to overall improved efficiency but also to increased emissions (Zhang & Smith, 1999).

When assessing the types of stoves used in the developing world there is, to date, no agreed set of stove testing protocols that have been devised under the guidance of a professional standards setting agency. Consequently, the majority of these protocols are not validated and certified by professional standard certifying bodies. This results in *ad hoc* protocols which are designed for a specific stove testing community or stove programme. This often leads to non-uniformity of the testing regimen, which makes it difficult to compare between stoves tested in different areas. The certification of these protocols could be useful in the support of legislature on air quality and for claims under the Clean Development Mechanism (CDM) projects. Hence, the drive should be on the development of robust stove testing protocols with the aim of having them validated and certified by certifying bodies, such as the American Society for Testing and Materials (ASTM) and TÜV Rheinland, for quality.

Many stove developers feel historically constrained to conduct all testing in terms of a standardised task. Tasks, being combinations of efficiencies, cannot be deconstructed to reveal the underlying thermal and emissions performance numbers (Robinson *et al*., 2010). The Indian National Programme for Improved *Chulhas*' (NPIC) failure illustrates the danger of relying on a single performance metric rather than a group of performance metrics that might give more information about the overall performance of the stove (Taylor, 2009). The results from such standardised tasks are used by project managers and funding agencies to compare stove performance and to select a stove suited for their programmes. The efficiency numbers reported by such comparisons are therefore important to stove developers who want to sell products or design services, or have stoves introduced as part of development aid or climate protection initiatives.

For the success of stove programmes, the stoves are tested in ways that reflect real-world uses of stoves using probable pots, lids, and fuels for which the stove was designed. Because both efficiency and emissions are highly dependent on stove operation (Baldwin, 1987), emphasis needs to be placed on the optimisation of the stove using fuels, cooking pots and the *end user* as these form a single cooking system. There is need to "*...assess the importance of a number of variables that are suspected to influence factors in emission*" (Ballard-Tremeer, 1997:9) and thermal performance tests of a fuel/stove combination. This is complicated by the changing stove testing protocols on the testing of emissions and thermal efficiency of a variety of stoves to meet the demand for quality. For example, there has been a great international debate regarding the relevance of laboratory situations versus practical situations (*controlled cooking test-CCT* and *kitchen performance test-KPT*). The difference between the two situations has often been posed in such a manner as to suggest that laboratory work cannot provide any guidelines for the development of efficient stoves (Johnson *et al.,* 2010; Roden *et al.,* 2009; Johnson *et al.,* 2008). Thus, the Engineers in Technical and Humanitarian Opportunities of Service (ETHOS) technical committee on stove testing methods was set up by specialists in both the laboratory and the field to develop, refine and update laboratory testing protocols that are robust and can simulate real-world cooking practices (Bond, 2007). This came in the realisation that both laboratory and field testing have their valued places in the overall assessment of global cookstove emissions. The ideas presented in this section will be reviewed in chapter 2.

1.3 Problem Statement

In light of the above discussion, a lack of adequate and appropriate stove performance and emission testing procedures and, the need for a new stove testing protocol have been identified.

1.3.1 Aim

This study aims to develop a set of testing protocols for determining thermal efficiency and emissions performance of domestic fuels and cooking devices to satisfy the rigorous performance specifications expected for claims under the Clean Development Mechanism (CDM) carbon trading market.

1.3.2 Hypothesis

A stove testing procedure that provides for testing of stove/fuel/pot combinations in a sequence of heterogeneous tests provides a better representation of thermal performance and emissions than existing protocols that are based on prescribed fuels and fuel loads, and single tasks.

1.3.3 Objectives

In order to achieve the above aims the following objectives were set out:

a. To critically evaluate the Water Boiling Test version 3.0 and other existing stove testing protocols.
b. Develop a set of criteria needed for a stove testing protocol for CDM certification.
c. To develop and evaluate a set of testing protocols for the quantification of combustion gas emissions and thermal performance from domestic fuels and cooking devices.
d. To document a set of standard operating procedures for all phases of the newly developed test procedure.
e. To carry out a comparative evaluation of paraffin fuelled stove *gas emissions* using the developed protocol.
f. To measure and compare the *thermal performance* of existing and improved paraffin and charcoal burning stoves using the new protocol.

g. To characterise *combustion efficiencies* from Top-lit Up-draft (TLUD), Bottom-lit Up-draft (BLUD) and Bottom-lit Down-draft (BLDD) coal burning stoves as a demonstration of the new protocol.
h. To conceptually evaluate the developed protocol in comparison with the Water Boiling Test version 3.0.

1.4 Justification of Study

This research study is embedded in a larger programme, which is a partnership between GIZ formally Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ)/Programme for Basic Energy Conservation (ProBEC), and the Sustainable Energy Technology and Research (SeTAR) Centre-University of Johannesburg. ProBEC assisted "...*stove builders to produce energy-efficient cooking appliances and trains new stove developers and producers*." (www.probec.org). The organisation was involved in stove research and testing "...*materials and manufacturing processes and supports the development of standards and test methods*" (www.probec.org) in the Southern African Development Community (SADC) region. ProBEC successfully facilitated the introduction and dissemination of energy-efficient technologies in low-income rural and urban communities in the SADC region.

BECCAP and ProBEC aimed to facilitate the development of markets for improved stoves, testing stoves for safety and energy efficiency, "...*finding entrepreneurs, helping to conceive and build different distribution models, realise carbon credits, and possibly financial buy-in from government-linked entities, such as the Central Energy Fund (CEF)*." (www.probec.org). In South Africa, ProBEC was mandated to help CEF in the roll out of the *Basa njengo Magogo* (*BnM*) method of lighting a fire. These projects aimed at reducing indoor air pollution (IAP) produced by burning solid and liquid fuels in simple, poorly designed stoves with inadequate ventilation.

In recent years, strong scientific evidence has emerged which suggests that indoor air pollution from domestic combustion of fuels contribute to excess mortality and morbidity (WHO, 2006). According to Barnes *et al*. (2009:5) "...*indoor air pollution exposure is a function of the complex interplay between household fuel patterns (Smith, 1987), appliances (Ezzati et al., 2000), housing design (Bruce et al., 2002) and human behaviour (Barnes, 2005)*." Most importantly, the unavailability of robust stove testing protocols has on occasion led to poor stove designs that are less efficient and more polluting than the baseline product. This has resulted in an increase in indoor air pollution causing respiratory complications in women and children who tend to spend more time indoors (Taylor, 2009; Barnes, 2006). Indoor air pollution (IAP) from solid fuels was classified the eighth top health risk worldwide, fourth top health risk in developing countries with high child mortality, third top health risk in India, after malnutrition and water bone diseases (WHO, 2002b). Indoor air pollution is responsible for killing 1.6 million infants, young children and women worldwide each year (WHO, 2002b) from exposure to harmful emissions from open fires and traditional stoves. Barnes (2006) contends that 420 000 or over 25% of these deaths happen in India, mainly in rural areas. The proportion is highest in sub-Saharan Africa (Rehfuess, 2006).

In a survey of India, Nepal and Africa, Terrado & Eitel (2005) found that elevated levels of particle air pollution are associated with acute respiratory infections (ARI), acute lower respiratory infections (ALRI) and with more complex diseases such as cardiovascular diseases and lung cancer. "*Acute lower respiratory infections accounts for approximately 14% of deaths amongst children less than five years in South Africa and is ranked, together with diarrheal disease, as one of the top killers of young children*." (Barnes *et al.,* 2004:543; von Schirnding *et al.,* 1991).

Domestic cookstoves are believed to contribute significantly to inventories of greenhouse gases (Zhang *et al.,* 2000). The lack of testing during stove design and iteration has led to an increase in ambient air pollution due to the accumulation of greenhouse gases (Taylor, 2009). One of the gases produced during the combustion of fuels in poorly designed cookstoves is carbon monoxide. There is a large amount of evidence indicating that carbon plays a role in climate change (Solomon *et al.,* 2009; Wigley *et al.,* 1996; Rind *et al.,* 1990). Elemental carbon, such as black soot, absorbs electromagnetic radiation and result in a direct warming of the atmosphere, with a global warming potential (GWP) of 680. Organic carbon tends to scatter electromagnetic radiation (GWP of -50) rather than absorbing it, resulting in a net cooling effect of the atmosphere (MacCarty *et al.,* 2008). According to Berntsen *et al.* (2006) as cited by Johnson *et al*. (2008:1217), "*The degree of impact depends on location and meteorological conditions*". However, various studies have indicated the reduction in carbon and greenhouse gas emissions due to the adoption and use of improved cookstoves (Berrueta *et al.,* 2008; Edwards *et al.,* 2004; Boy *et al.,* 2000). According to Zeng *et al*. (2005) about 50 million tonnes of CO_2 are avoided annually in China due to the introduction, adoption and use of improved cookstoves. Visser (2005) contends that before improved stoves are introduced, data on expected fuel savings from improved cookstoves against baseline should be available.

This study is significant in that there is now a growing interest for accurately specifying stove performance of solid and liquid fuels in the developing world under the CDM carbon trading market. There has been a call for stove testing protocols that simulate real-world use and can be used for certifying stove thermal and emissions performance for greenhouse gases (GHG) and air quality management accounting purposes. This came through the realisation that there are limited "*...data available on emissions from numerous types of cookstoves used in the developing world*" (Zhang *et al.,* 2000:4537). For example, "*...few measurements have been made to determine emission factors for biomass stoves in developing countries (Smith et al., 1993). Emission factors* *from other fuels (e.g., coal, kerosene) as commonly used in developing-country households are not well characterised. Therefore, measurements of GHG emission factors from a range of fuel/stove combinations…would provide a baseline for understanding the potential for reduction in GHG emissions due to various mitigation measures, such as fuel switching, in the household sector.*" (Zhang *et al.,* 2000:4537-8).

"*Although work on improving biomass and liquid fuel stoves has been ongoing for many years, much of the effort has been project based, often donor-led, and mainly directed at reducing fuel consumption primarily for economic and environmental reasons*." (Boy *et al*., 2000:23). In these efforts the fuel-stove-pot-user nexus was completely ignored. The lack of robust testing protocols which addressed the fuel-stove-pot-user nexus resulted in the failure of most stove programmes earmarked for the poor in the developing world (Taylor, 2009). Such an example include: the Indian National Programme for Improved *Chulhas* (NPIC), which according to Duta *et al*. (2007), "*...achieved neither a significant sustained improvement in fuel efficiency*" (Smith *et al*., 2007:6) nor saved time, nor a reduction of deforestation. There was little evidence that the reduction in indoor air pollution was achieved (Smith *et al.,* 1983).

1.5 General Approach in the Study

The general approach used in this study is both confirmatory (hypothesis testing) and developmental (focused on corrective action). The study discusses the development of testing protocols for use with both vented and unvented cookstoves.

Stoves were tested under laboratory conditions at the SeTAR Centre situated at the University of Johannesburg. The stoves were tested for thermal and emissions performance using the 'direct' hood method (Ahuja *et al.,* 1987). "*The approach has been to design the emissions monitoring system such that it can be operated simultaneously with the determination of thermal performance. Thus, trade-offs between thermal and emissions performance can be investigated*." (Ahuja *et al*., 1987:251). Eight fuel/stove combinations (three paraffin stoves, three coal stoves and two charcoal stoves) were tested for greenhouse gas emission factors, thermal performance and efficiency to highlight the effectiveness of the developed protocols. The *Basa njengo Magogo* (*BnM*) method was used to illustrate improvements in the lighting of the *imbaula* against the baseline (classical fire lighting method).

"*Efficiency and other performance characteristics of the stove are calculated from fuel mass and evaporated water mass by placing the whole stove on a digital weighing scale under a gas collecting hood. The water temperature and the flue gas temperatures will be measured using thermocouples*" (Ballard-Tremeer, 1997:116) attached to the Testo® 350XL/454, a portable flue gas analyser system for complex thermal processes. Emissions to be monitored included: carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_2, NO_X), hydrogen (H_2), oxygen (O_2), sulphides (SO_2, H_2S), and sulphur (S). The combustion efficiency of the device was calculated using the ratio of carbon monoxide to carbon dioxide in the stack.

Other collected data included "*...water temperature changes, amount of water vapour generated, and amount of fuel burned. These are necessary to determine thermal parameters such as burn rate and overall thermal efficiency of each fuel/stove combination.*" (Zhang *et al*., 2000:4541). The total emission mass per standard task were determined from the calculation of the concentrations of emissions emitted during the heating up phase and during the simmering phase at different power settings of the stove.

1.6 Scope of the Study

The scope of the study is limited to the development of new stove testing protocols appropriate to a range of solid fuel (charcoal and coal) and liquid fuel (paraffin) stoves in the African context, rather than to do an extensive study of each fuel/stove combination. Comprehensive results are presented for the paraffin stoves and a preliminary set of results is given for solid fuel stoves, with no attempt made to do an extensive and rigorous evaluation/study of the stoves. Through presentation and discussion of representative results, we illustrate how the protocols can provide essential information for the rating, comparison and ranking of a stove's performance. The critique on existing protocols highlighted in this study is to present to the reader a point of departure, demonstrating how the need for new and robust testing arose. The protocols developed here are laboratory based. Extensive tests comparing the laboratory results with home-based tests is an important future task, but not within the scope of the thesis. The arguments and examples contained herein are limited to paraffin, coal and charcoal stoves. Although, particulate emissions from wood and coal stoves are important for human health and climate reasons, they are not included in this study as appropriate apparatus was not yet available in the laboratory.

1.7 Chapter Overview

Chapter 1 introduces fuel/stove use in developing countries in Africa and domestic stove testing programmes in general. A problem statement is formulated, the domain of the study specified, aim and objectives set out. A justification of the study is presented and the general approach to the study is outlined.

Chapter 2 presents a literature survey of stove testing programmes and stove testing methods and their limitations. A detailed review of failure of some stove testing programmes is reported. A variety of methods for gathering data is reviewed and critiqued. The development of Standard Operating Procedures (SOPs) is highlighted.

In Chapter 3 innovative developments in stove testing protocols are motivated and described. Apparatus used to carry out these protocols are described in detail. A range of seven paraffin and solid fuel stoves that were evaluated for thermal and emissions performance are described in terms of their characteristics. The elements of the test procedure making up a full test protocol are identified and described including emission factors, thermal performance and fuel consumption. Aspects of quality control and documentation of protocols and standards are described.

Chapter 4 presents and discusses a motivation for the *Heterogeneous stove Testing Protocol* (*HTP*) and standard operating procedures. Results from gas emissions from a variety of paraffin, charcoal and coal stoves are presented in detail as examples of how the protocols are applied in practice, and of typical emissions and thermal performance results. Thermal parameter and rated system performance results of three paraffin stoves are presented in some detail. This data is useful for the ranking of fuel/stove combinations. A conceptual comparison of the *HTP* and the Water Boiling Test Version 3.0 is presented at the end of the chapter.

Chapter 5 presents a summary of the main findings of the study. The chapter ends with a conclusion with reference to the hypothesis of the study and recommendations for further study.

CHAPTER TWO

A literature survey of stove testing programmes and stove testing methods and their limitations is given. A detailed review of failure of some stove testing programmes is reported. A variety of methods for gathering data will be reviewed and critiqued. The development of SOPs is highlighted.

2. Stove Testing: Antecedents, Needs and Precedents

The development of domestic stoves "*...is not a recent phenomenon. Within the last one hundred years, wood-burning stoves were adopted by middle and upper-income families*" (Barnes *et al*., 1994:3) to meet their basic energy needs, such as cooking and space heating. "*Supporters and practitioners of Appropriate Technology were the first to recognise the potential of wood-burning stoves.*" (Bussmann, 1988:1). Their main goal was to develop improved biomass burning stoves and disseminate them in an effort to lessen the burden on forest resources. The group failed to set up any significant stove projects of sizable magnitude. Prasad (1983) pointed out that the field of Appropriate Technology was marred with "*...a lack of professionalism and did not recognise the need for it.*" (Bussmann, 1988:1). They advocated the adoption of improved stoves on a massive scale and spread by diffusion and yet the mass dissemination never took place (Tampleman, 1982).

Stove testing is still not a common practice in many domestic energy programmes. Most projects have attempted to monitor energy consumption at family level, using ambiguous questionnaires to encourage the desired answers (Bussmann, 1988). It is thought that it was in this period that the myth of 50 % savings with improved stoves arose. According to Leach & Gowen (1987), "*...these programmes also often ignored the complex interrelationship among the variables determining the energy consumption.*" (Bussmann, 1988:3).

In the early publications[4], testing procedures have been suggested and they have established the performance of the stove by expressing the performance using a single metric referred to as 'the efficiency'. The cookstoves were judged and rated on their efficiency or on their fuel consumption per task accomplished (Ballard-Tremeer & Jawurek, 1996). With the efficiency numbers, there was hardly any information available on power, upper or lower calorific value, fuel (size, moisture content), pot sizes, evaporated water, and number of tests and duration of tests (Taylor, 2009). The same applied to fuel consumption numbers where it was often unclear how these numbers were

[4] These publications are from the early 1980s to the early 2000s when the WBT was first developed for the Household Energy and Health Programme, Shell Foundation.

obtained from tests (how the tests were done), surveys, and how they were estimated (Pemberton-Pigott, 2009; personal communication).

The system of a wood-burning cookstove is too complex to be captured using a single metric of performance. Field workers argued that efficiency numbers were of no use because their meaning could not be appreciated by people using the stoves in the real world, especially in the developing world. On the other hand, laboratory workers argued that fuel consumption numbers and the way they were obtained were not scientific, and of no use in understanding stove behaviour.

From the early 1980s attempts were made to resolve the controversy, resulting in a provisional standard in stove testing aimed at ensuring the technical performance in addition to the socio-economic and viability of stoves (VITA, 1985). This standard method resulted from a meeting of stove experts, at which both field and laboratory workers were represented.

At the Seventh Woodstove Seminar held in Belgium "*...in 1982, it was agreed that a systematic effort should be undertaken to reach as wide a consensus as possible on field testing of woodstoves*." (VITA, 1985:3). At the seminar the majority of the participants felt that too many approaches to testing were being used, resulting in misunderstandings that hindered comparison of results (Bussmann, 1988). "*An informal international working group met in Marseille in 1982 to develop a standard for field testing of woodstoves. The group agreed that there was an urgent need to for an internationally acceptable standard. The Marseille group agreed that the evaluation concepts and reporting specifications could be fixed in the standard test procedure and that food, fuels and pots could be specified in local standards*." (VITA, 1985:3). The procedure was written and published for comments and later on re-written for use by different stove testing and designing institutions around the globe, and came to be known as the *VITA Water Boiling Test* (VITA, 1985).

This standard was followed for a while. However, it was soon realised that it was too much of a compromise and other organisations came up with their own modified methods. Bussmann (1988) contends that the VITA procedure is a mere compromise and far from ideal: "*The methodology fails to highlight the reasons why stoves perform differently and neglects the existing parameters which determine the fuel savings of a stove*" (Bussmann, 1988:5). The testing method is not suitable for design purposes as it neglects critical parameters that are important in stove designing.

To address the shortfalls of the Water Boiling Test (WBT), tests such as the controlled cooking test (CCT) and the kitchen performance test (KPT) were developed and introduced. The controlled cooking test (an efficacy test) was designed to measure "*...fuel consumption associated with the performance of a specific cooking task. However, it is difficult to compare across regions or food types*." (Berrueta *et al.,* 2008:861).

The kitchen performance test "*...was designed to evaluate family fuelwood consumption under real usage conditions* (in situ) *of stoves in local communities*" (Berrueta *et al*., 2008:861), over several days. "*The fuel efficiency comparison relies on consumption data from households in which the cooking methods are used for daily household activities.* The transition from Water Boiling Test to kitchen performance test *brings an improved understanding in the situated practice, but introduces an increase in uncertainty*." (Granderson *et al.,* 2009:6). Unlike the Water Boiling Test, the kitchen performance test has undergone relatively slight changes and systematic evaluation. "*This testing method is difficult to perform and requires more resources and cooperation of local users*." (Berrueta *et al*., 2008:861). Bailis *et al*. (2004) acknowledge the difficulties of implementing field assessment such as the KPT. The CCT and the KPT "*...have seen more limited applications since their inception*" (Bailis *et al.,* 2007a:59) while variations of the VITA WBT have become a popular standard, "*...for example, much of the research on stove emission relies on a version of the WBT to simulate the cooking process while measurements are taken*." (Bailis *et al.,* 2007a:69).

In spite of documented problems associated with use of the three stove performance tests (the Water Boiling Test (WBT), the controlled cooking test (CCT), and the kitchen performance test (KPT)) little research has focused on improvements and development of new stove testing methods (Johnson *et al.,* 2010). In light of this argument, there is a growing need to focus on the improvements of stove testing methods. Other organisations and stove testing protocol developers are compelled to develop alternative sets of protocols and standards to augment efforts from existing protocols.

2.1 Criteria for a Testing Protocol for CDM Certification

The "*Clean development mechanism (CDM) is an arrangement under the Kyoto Protocol allowing industrialised countries with a greenhouse gas (GHG) reduction commitment to participate in emission reducing projects…The purpose of the CDM as defined under Article 12 of the Kyoto Protocol is to assist developing countries in achieving sustainable development, while contributing to the stabilisation of greenhouse gas concentrations in the atmosphere*." (www.bci.co.in).

"*Improvements in performance testing are critical to derive more representative estimates of emissions, given the current importance of stove performance tests as a basis for global climate prediction models and IPCC inventories*". (Johnson *et al*., 2010:368). Emissions from cookstoves contribute significantly to regional estimates of carbon aerosols and inventories of greenhouse gases (Johnson *et al.,* 2010). Improved cooking stove projects in the developing world are being asked to reduce deforestation, improve health, and slow climate change. "*Estimation of emissions from cookstoves is important in assessing the global warming benefits of installing improved stoves, and changes in fuel type*." (Johnson *et al.,* 2008:1207). They can be useful in the modelling of atmospheric greenhouse gas concentrations (Tan *et al.,* 2004). These requirements reinforce the need for thorough testing and verification of performance (MacCarty *et al.,* 2010). More importantly, they reinforce the need for robust testing protocols that can be used for the inter-comparison of a variety of fuel/stove combinations and the certification of greenhouse gas emissions for air quality management purposes.

This section seeks to identify a set of criteria that can be used in the development of stove testing protocols which "*...provides more relevant information for global climate models and inventories, while providing a means to recreate representative emissions profiles in a laboratory setting for technical analyses*." (Johnson *et al.,* 2010:368). The critical issue is not that the task or cooking activity is representative but that the burn cycle is representative of that which occurs during daily cooking activities in homes.

The following criteria will be used to evaluate stove testing protocols for CDM certification:

- *Does the protocol measure greenhouse gas emissions over an entire cycle that is representative of real-world uses of stoves?*

It is contended that an ideal protocol should be able to analyse real-time combustion efficiencies and emissions rates over an entire burn cycle "*...based on replication of the distribution of emission rates and combustion efficiencies seen during daily cooking activities in homes*." (Johnson *et al.,* 2010:368). The non-representative carbon emissions and efficiency estimates found using laboratory based tests should not be surprising given that controlled burn cycles for specific tasks cannot encompass the variety of daily stove use activities, with up to 90% of stove tasks in some regions not involving boiling water (Johnson *et al.,* 2010). Since efficiency varies significantly as a function of power output during the different phases of the burn cycle, a single efficiency is not a good performance indicator (Johnson *et al.,* 2010; Prasad *et al.,* 1985). Using real-time emission rates and combustion efficiencies, it is possible to substantiate combustion efficiencies during discrete burn events, typical of stoves used in real-world use.

- *Does the protocol allow testing of fuels typical to the target area?*

Existing protocols for solid fuels do not allow for the testing of fuels typical to a target area and often prescribe the moisture content; size of fuel; and species of wood to use in wood burning stove; in an effort to derive a standardised test. This result in tests that are not representative of real-world uses of stoves and the emissions estimates thereof are illusory. The protocol should allow for the testing of fuels typical to the target area or to local customs. The tests can be carried out using fuels specified by the stove manufacturer or as commonly used in the homes. The same applies to the size (for solid fuels) and the volume (for liquid fuels). The load should be typical of real-world uses of the stoves.

- *Does the protocol allow for the identification of stove design weaknesses and advantages?*

Stove testing protocols have been used in the design, modification and improvements of existing stoves. The Water Boiling Test was designed to give feedback on the design of new technologies (Bailis *et al.,* 2007a). The tests are carried out on *high* power and an indeterminate *low* power setting, since an open lid pot is used for the simmering phase thus requiring a somewhat high fire-power to keep the water simmering. However, the test procedure does not involve testing of a stove across its full range of power setting thus design defects on other power settings are not detected during the design phase. The protocol should allow for the identification of stove design weaknesses and advantages using real-time feedback on stove design during the different stages of a burn event. The distribution-based approach (Johnson *et al.,* 2010) for stove performance testing may allow estimation of CO_2 equivalent from a fuel/stove combination and products of incomplete combustion (PIC) emissions associated with different parts of its burn cycle. Ideally, this is done to target for improvement those parts that produce the most CO_2 equivalent and products of incomplete combustion (PICs).

- *Does the protocol allow for the expression of results in a normalised manner for direct comparisons between different fuel/stove combinations?*

A challenge in testing is comparing between the performances of a variety of stoves designed for different tasks using a variety of fuels. A stove has to be evaluated for emissions and thermal performance using fuels and tasks it was designed for. The use of a standardised task to compare between stoves is deceiving and often rates inherently poor a fuel/stove that is not designed for that particular task. The designed protocol should be able to allow for the expression of results in a normalised way so that direct comparisons between different fuel/stove combinations can be made. Preferably, each stove type should be treated as an independent technology with corresponding emission factors in determination of carbon savings by an improved stove programme.

- *Is the protocol certified by certifying bodies?*

Stove testing protocols need to conform to certain standards if they are to be useful in the development of efficient stoves, and the reduction of greenhouse gases and other obnoxious emissions of incomplete combustion. Certification of stove testing methods has become important due to the growing interest in the potential to trade carbon offsets from improved stove programs on carbon markets for voluntary reductions, or as part of international accords. The majority of these widely used stove testing protocols are not validated and certified by professional standard certifying bodies. This results in *ad hoc* protocols which are designed for a specific stove testing community or stove programme. This often leads to non-uniformity of the testing regimen, which makes it difficult to compare performance of stoves of varying types and from diverse regions of the globe (Taylor, 2009). Certification of such protocols could be useful in the support of legislation on air quality and for claims under the clean development mechanism (CDM). Hence, the drive should be on the development of robust stove testing protocols with the aim of having them validated and certified by independent certifying bodies.

2.2 Challenges of Earlier Developing Country Improved Stove Programmes

Well designed cookstoves can bring positive benefits to the end user. However, simply introducing improved cookstoves does not guarantee uptake of improved products and that positive outcomes could be achieved (Bailis *et al.,* 2007a). Design, socio-economic and cultural preferences play a pivotal role in the successful adoption of improved cookstoves. Programmes focusing only on dissemination of cookstoves often did not take into account local customs and the economic background of the targeted areas. Stove programmes, on the other hand, have shown that superior efficiencies, demonstrated by laboratory tests, "*...are not sufficient to guarantee a widespread dissemination of stoves. Rather, the stove has to be competitive with the traditional stove in a multitude of factors, such as ease of use, safety, time-saving and attractiveness so that the user clearly perceives the benefits it creates*." (Kuhnhem, 2003:5). Taylor (2009) cites poor testing due to the lack of robust stove testing protocols as the impetus for the failure of the stove programmes. Notable failures are the Lorena and the Indian National Programme on Improved Cookstoves (NPIC) stove programmes (Johnson *et al.,* 2010; Taylor, 2009; Smith *et al.,* 2000a).

2.2.1 The Lorena stove programme

In the late 1970s and early 1980s there developed an increasing awareness, among governments, humanitarian organisations and non-governmental organisations, of the trend toward deforestation and domestic fuel shortages throughout the developing world (Taylor, 2009). The Lorena stove programme was introduced in 1976 in Guatemala to reduce fuelwood consumption in the preparation of food. The Lorena improved stove was named from the materials from which it was manufactured: *lodo* (clay) and *arena* (sand). The idea was to build a stove that used less fuel than the three stone fire. "*…the Lorena stove's specific dimensions depended on each user's preferences and resources. As a result, stoves were round, square, rectangular, or even triangular in shape to fit into corners. Stove size and shape depended on space and available materials. The firebox, diameter of internal passages, opening for adding firewood, and chimney height were not standardised; no special tools were needed for construction; and measurements were made using hands and fingers*." (Alvarez *et al*., 2004:10). Hence, the real world implementation of the Lorena stove programme did not deliver the intended benefits – in many instances the stoves used more fuel than the three-stone fireplaces that they replaced.

After building a new stove for a family, an aid worker would return after some weeks and ask vague and quite possibly leading questions, about the stove. As such, fuel savings of fifty percent were reported for each stove (Bussmann, 1988; Eckholm *et al.,* 1984; Smaller, 1981). When the stoves were finally tested against a three-stone fire, the thermal efficiency of the stoves were demonstrably lower than the three-stone fire and families using the stoves used more fuel than those using the three-stone fire (Taylor, 2009, Krugmann, 1987; Foley & Moss, 1983). Taylor referred this performance lapse to lack of appropriate testing: "*The designers had made an obvious mistake in conflating heat capacity and thermal resistance, but the real practical failure was not the misunderstanding of heat transfer; it was a lack of appropriate testing*." (Taylor, 2009:12).

2.2.2 The National Programme on Improved Cookstove (NPIC) stove programme

The National Programme on Improved Cookstoves (NPIC) was started by the Department of Non-conventional Energy Sources (DNES), Government of India in 1985, aimed at enhancing the energy efficiency of biomass burning and eliminating the smoke from the kitchen environment. "*The objectives of the NPIC were fuelwood conservation; removal/reduction of smoke from kitchens; reduction of deforestation and environmental degradation; reduction in the drudgery of tasks performed by women and girl-children and their consequent exposure to health hazards; and employment generation in rural areas.*" (Kishore & Ramana, 2002:48).

"*Improved cookstoves (Chulhas) have been in vogue in India since the late 1940s*." (Kishore & Ramana, 2002:47). The "*Chulha is a simple, modular concrete-block stove covered in brown clay. It features two potholes: one for circulating hot air for steamed foods such as rice, and the other for heating flat pans holding chapatti (fried bread) and similar dishes. A critical design element of the Chulha is a chimney fitted with a special filtering device made of slotted clay tablets to trap toxic particles*." (Beck, 2009: www.designobsever.com). There are no pot raisers, and because the pots sit flush on the potholes, the flue gases do not escape into the kitchen, but are taken out of the house. "*The chimney is equipped with a small trap door that affords easier cleaning from within the house*." (Beck, 2009: www.designobsever.com). Thus, the *Chulha* has the potential to significantly reduce indoor air pollution.

Concerted efforts to promote this technology in rural areas began only in the early 1980s in the wake of the rural energy crisis (Venkata, 1996). The program disseminated approximately thirty million improved stoves between 1993 and 1998, replacing use of open hearths or three stone fireplaces. "*The Ministry of Non-Conventional Energy Sources (MNES) reported a national savings of 120 million metric tonnes of fuelwood with yearly savings of 9% of the annual fuelwood demand due to the adoption and use of improved stoves in this period.*" (Taylor, 2009:13; MNES, 1993). The reported savings of the stoves depended on the following assumptions: life expectancy of the stoves is indefinite; a *Chulha* saves fuelwood at an average rate of 700 kg y^{-1}, irrespective of its age, type and region; and the monetary value of biomass saved is Rs400 per tonne (Kishore & Ramana, 2002; MNES, 1993).

From the research carried out by Kishore & Ramana (2002), it was shown that the real benefits from the NPIC are likely to be lower than claims made in the annual reports of DNES. The expected lifespan of the stoves installed was found to be less than three years and yet the assumptions were made to the effect that the life expectancy of the stove was indefinite. Consequently, it meant that by 1998 there were likely to be between four and six million *Chulha* stoves in use, rather than the 30 million hypothesised (Taylor, 2009; Kishore & Ramana, 2002). "*The NPIC estimates on fuelwood savings appeared to have been based on a comparison of thermal efficiency of the improved stoves against the traditional stoves determined through the Water Boiling Test (WBT)*." (Taylor, 2009:14).

The programme achieved neither a significant sustained improvement in fuel efficiency nor saved time, nor a reduction of deforestation[5] (Duta *et al.,* 2007). There was little evidence that the reduction in indoor air pollution was achieved (Smith *et al.,* 1983). Boy *et al*. notes that "…*with the exception of countries like Kenya (WHO, 1992) and China (Smith et al., 1993), improved stove programmes have met with limited success, with stoves falling into disrepair or being abandoned.*" (Boy *et al*., 2000:23). "*Most of this work was ill-coordinated and as a result did not bring about substantial change in policy, donor commitment and most importantly, action in those countries and poor communities that were worst affected.*" (WHO, 2002a:8).

2.3 Significance of Stove Testing

The results of the Lorena stove and the Indian NPIC programmes show the need for testing methods that reflect real-world uses of fuel/stove combinations, of both baseline reference stoves and of purported improved stoves. Such testing methods are important for a number of aspects in the development and dissemination of improved domestic cooking devices which are more energy efficient and less polluting.

2.3.1 Stove performance comparative analysis

Testing can be used to compare different stoves when trying to choose between models. "*Baldwin (1987) recommends lab-based tests for comparing and optimising different dimensions and other design details of the stove. Lab-based tests are more appropriate when comparing stoves that are used in different regions of the world*." (Bailis *et al*., 2007b:16). Stove users would like a way of distinguishing the benefits of one stove over another at the time of purchase. This point to the need for a test that is robust and capable of meaningfully allowing such comparisons. "*A test that will*

[5] Alternative arguments have been advanced that most deforestation is caused by clearing for agriculture and logging, not by wood collection. Firewood collection causes forest degradation only in certain places, particularly in areas of high population density, around cities, on fragile and sloping lands, and where common property resources are not managed well (Heltberg, 2001).

allow a meaningful comparison between stoves must either specify a fuelling and operating regime that works for a large variety of stoves, or must include some way of accounting differing operating and fuelling regimes." (Taylor, 2009:18). In order to know the impact the stoves will have on the users, the stoves have to be measured under conditions of realistic use.

2.3.2 Stove design purposes

Tests such as the Water Boiling Test and the controlled cooking tests are less representative of real-world use of stoves. They are appropriate at the early stages of stove development to compare various technical aspects of stove design. "*These controlled tests are useful at the designing phase, with the goal of determining whether the stove is functioning as intended. Testing should be used to determine what impact the alteration had on performance.*" (Taylor, 2009:16). This design iteration is recommended by a number of publications on stove design and testing (Taylor, 2009; Todd, 2001; Bussmann, 1988; Baldwin, 1987; De Lepeleire *et al.,* 1981). If the same procedure is used each time, the data from one design iteration of the stove can be directly compared to the data from a different iteration.

To ensure that the test results are meaningful in the context of CDM emissions reductions of indoor air pollution, the test must be based on one or more key use scenarios that are typical of the cooking culture by the potential users. It is important to include market studies aimed at understanding the needs and desires of the potential user base in order to determine the weight that should be given to any single performance metric. For example, if the cooking culture is based on *high* power for cooking and *low* power for space heating and warming food, a test based exclusively on *high* power operation will not provide meaningful information.

2.3.3 Certification purposes

Since combustion stoves contribute significantly to inventories of greenhouse gases, there is need to come up with benchmarks for stove thermal and emissions performance for use in emissions inventories for climate modelling. In recent years "*...there has been a growing interest in the potential to trade carbon offsets from improved stove programmes on carbon markets for voluntary reductions, or as part of international accords. To meet these trading schemes, methods meeting minimum accountability standards for quantifying their impact on GHG emissions are needed.*" (Johnson *et al.,* 2007:11).

The World Health Organisation has set targets for indoor air quality, and many governments have instituted regulations intended to persuade stove manufacturers to meet the WHO targets. In South Africa, for example, there are strict limits on the acceptable combustion efficiency of paraffin stoves, intended to limit indoor exposure to carbon monoxide. The South African Bureau of Standards (SABS) is the statutory body mandated for the promotion and maintenance of standardisation and quality of commodities and services. The SANS 1906:2009 states that if a paraffin stove is operated at the highest possible power setting, it should not produce over 0.03g of particulate matter per minute and that the combustion efficiency ($CO:CO_2$ ratio) should not exceed 2% volumetric ratio.

These standards are useful for the certification of fuel/stove combinations to meet the interest of financiers, and the proof of emissions performance for carbon trading. "*The most common performance metrics currently being used in this capacity are combustion efficiency, thermal efficiency, task-specific fuel consumption, safety, CO emissions, and particle emissions, derived from standardised water boiling procedures*" (Taylor, 2009:19).

2.4 Methodologies for Thermal and Emissions Performance Testing of Cookstoves

There have been a number of methods used in the determination of thermal and emissions performance of stoves. Studies for the determination of thermal efficiency of a fuel/stove combination have been reported, using a version of the standard Water Boiling Test developed by the University of California Berkley (Johnson *et al*, 2010; MacCarty *et al*, 2010; Roden *et al.,* 2009; Johnson *et al.,* 2008; Boy *et al.,* 2000). Emissions performance was evaluated using either one of two methods – the *chamber method* or the *hood method* – used simultaneously with the Water Boiling Test.

The chamber method, first suggested by Ahuja *et al*. (1987), was developed in an attempt to reduce the cost and complexity, and to avoid some of the errors assumed to be inherent in the direct hood method. "*The method requires no ductwork and air flow calculations. In principle, it can be done in any chamber or even in a remote village house where the ventilation conditions are relatively constant over the period of measurement. The stove is put through a cooking cycle in the room and the pollutant concentrations are monitored within the same room…Airflow conditions around the stove can be simulated much more closely with this method*." (Ahuja *et al.,* 1987:250). The method also entails that the fire is removed from the room on the completion of the water boiling sequence, while the gas or "*...smoke concentrations continue to be measured. The air exchange rate is calculated from the measurements of the pollutant concentration decay*." (Ballard-Tremeer & Jawurek, 1999:482).

There are disadvantages of using this method. Due to the stratification of smoke in the room, the method requires a constant mix of the air to assume a steady state condition since the air exchange rate has a significant effect on the results (Ballard-Tremeer & Jawurek, 1999). In addition, "*...the operators are subjected to the smoke while tending the stove and instruments inside the room.*" (Ahuja *et al.,* 1987:250).

The method can also be done in a chamber. This method is based on a single compartment mass balance model. The method requires that the stove be operated according to a pre-defined task, with all emissions ducted into and captured in a dilution chamber, and average concentrations of the pollutants in this chamber are measured at the end of the task. "*Fans are used to mix the air in the chamber to avoid stratification of the gases or smoke*." (Ballard-Tremeer & Jawurek, 1999:487).

"*The determination of emission source strength using the chamber method requires the solution of a first order differential equation, which is formulated from a mass rate balance within the chamber*" (Ballard-Tremeer & Jawurek, 1999:482; Ahuja *et al*, 1987). An alternative approach to the chamber method will involve collecting the emission through ductwork. The collected pollutant concentrations are then normalised to a known reference value.

For the purposes of this study, the hood method and the Water Boiling Tests will be reviewed in detail in the following sections.

2.4.1 The hood method

This particular method entails that the tested device is placed under a hood, into which all the flue gases are drawn by thermal drafting, with or without assistance of forced draft by a fan, making the unvented device similar to a ducted emission source (Ahuja *et al.,* 1987). This method (sometimes called the *direct* measurement method) has been used in the developing world for studies of unvented cookstoves (Johnson *et al.,* 2008; Bhattacharya *et al.,* 2002; Davidson *et al.,* 1986) and paraffin space heaters (Lionel *et al.,* 1986). "*Butcher et al. (1984) attempted to design a low cost, simple emission measurement system in this way. They measured CO and total suspended particulates (TSP) passing through the hood at a measured flow rate. Nangale (1992) used the same method and apparatus to determine hydrocarbon activity in the flue gas by passing the gases through cold water and measuring the change in acidity of the water*." (Ballard-Tremeer & Jawurek, 1999:482). Ballard-Tremeer & Jawurek (1999) compared the emissions and efficiencies of five rural cookstoves using this method. They found that the effect of the hood on the emission was small (measurable only for CO at high extraction rates). In 2003-2004, Aprovecho Research Centre designed an emissions collection hood based on findings from Grant Ballard-Tremeer's doctoral thesis (Ballard-Tremeer, 1997). Since the design of the hood, over one thousand Water Boiling Tests have been performed at Aprovecho Research Centre in evaluations of various cooking technologies and design improvements to projects (MacCarty *et al.,* 2010).

The method requires a constant and steady state exhaust flow rate during the entire burning test in addition to *isokinetic* sampling for larger particles. Emissions can be calculated by "*...either directly measuring the air flow in the hood or by estimating the air flow through mass balance* *calculations using nitrogen and carbon* as reference gases*. The dilution of outside air can be estimated and the pollutant emissions per unit fuel burned can be determined.* A *variant of this approach has been used in which ratios of pollutants are monitored without any determination of air flow for stove/fuel combinations, such as gas cookstoves*" (Ahuja *et al.,* 1987:250; IS 4246:2002) for which steady state conditions can be achieved.

Limitations of the method

Several difficulties are apparent with the hood method. The method requires the determination of the air flow rate in order to account for dilution of captured air stream by ambient air (Ahuja *et al.,* 1987). The determination of air flow requires a significant increase in the complexity and cost for the facility, and the complexity requires that the test rig is often limited to a laboratory setting. This type of test rig may not be suitable for mobile field trials, although it is possible to design small test rigs to use in field evaluations of fuel/stove combinations. A serious "*...problem is the potential for the mechanically induced air flow to alter the combustion characteristics of the stove. The potential for the hood to physically interfere with the tending of the cookstoves during measurements*" (Ahuja *et al.,* 1987:250) is a practical impediment in field trials.

"*For those stoves with flues, the sampling probe was placed inside of the flue or inside of a hood which was placed over the end of the flue*." (Zhang *et al.,* 1999:355). This may result in a measurement error since all emissions may not pass through the chimney or the hood. For natural draft hoods, it is possible that not all emissions pass through the chimney during parts of the burn cycle. Further, determining the excess air level in the chimney, upon which the emission factors and thermal efficiency calculations depend, is not as accurate using a hood because it is not possible to know if the O_2 in the hood came from ambient air or passed through the stove. However, Zhang *et al*. (2000) did not observe significant differences when sampling directly from "*...a vented stove chimney or from a hood placed over the entire vented stove and flue*." (Johnson *et al.,* 2008:1210). "*Prior studies using emission hoods found no change in combustion efficiency at lower hood levels and higher extraction rates*." (Johnson *et al.,* 2008:1209; Smith *et al.,* 2000b; Ballard-Tremeer, 1997).

2.4.2 The Water Boiling Test (WBT)

The majority of fuel/stove thermal performance and emission factors have been derived using controlled[6] testing procedures in simulated kitchens (Smith *et al.,* 2000b; Zhang *et al.,* 2000). Current Inter-governmental Panel on Climate Change (IPCC) stove emission factors and those

[6] An alternative to this method is the *uncontrolled cooking test* which entails that the meal is not constrained and the cook is free to prepare what they want, how they want, with the only measurements being that of the firewood used and the final mass of food cooked as part of an actual household meal (Robinson *et al*., 2011).

often cited in emissions inventories for climate modelling are ultimately derived from the Water Boiling Test (Johnson *et al.,* 2007). The WBT was developed as a standard international method to compare efficiencies of different fuel/stove combinations (VITA, 1985). It was originally designed for wood-burning stoves. These tests provide qualitative and quantitative results about stove performance (Rani *et al*., 1992). However, "*...to determine the effect of various design modifications on the performance*" (Rani *et al*., 1992:919) of fuel/stove combinations, and to optimise their performance, more rigorous and detailed test procedures may be necessary (Makonese *et al*., 2010a).

The Water Boiling Test (WBT) intends to be a simulation of the cooking process; thereby assisting stove designers understand how much fuel is needed to complete a cooking task (Bailis *et al*., 2007b). The test starts with a *high* power boiling phase to bring a measured amount of water to a quick boil. Pre-weighed fuel is added as needed at *high* power setting to bring the water to a quick boil in a standard pot. This part of the test is often referred to as *cold start* since the tester begins the test with the stove at room temperature. "*The tester then replaces the boiled water with a fresh pot of cold water to perform the second phase of the test*." (Bailis *et al.,* 2007b:2). The second phase is referred to as the *hot start* high power test. In this phase tests are carried out immediately after completion of phase 1, while the stove is still hot. It entails the use of a pre-weighed fuel batch used similarly to boil a measured amount of water in a standard pot. The intent is to identify the differences in performance between a hot stove and a cold stove. A simmering low-power phase follows. "*The tester determines the amount of fuel required to simmer a measured amount of water*" (Bailis *et al.,* 2007b:2) for 45 minutes, simulating the long cooking of rice and legumes in real-world uses of fuel/stove combinations (in certain parts of the world). Thus, the "*WBT assesses the thermal efficiency, the fire-power, and the specific fuel consumption of a stove, where thermal efficiency is a ratio of the work done by heating and evaporating water to the energy released by burning wood*." (Berrueta *et al.,* 2008:861).

One other metric used to characterise stoves in the WBT procedure is the *turn-down ratio.* The turn-down ratio is reported as a positive real number equal to the fire-power of the stove at *high* power divided by the fire-power of the stove at *low* power. Data handling and calculations for the WBT Version 3.0 are routinely carried out using a publically available Microsoft Excel® spreadsheet (The Shell Foundation HEH Project WBT data and calculation form: http://www.berkeleyair.com/publications/cat_view/42-publications).

Due to the need for evaluation of other fuel/stove technologies, and to regional differences in commonly used fuels and cooking practices, there have been variations to the standard Water Boiling Test. Notable variants are as follows:

- The Indian standard Water Boiling Test developed by the Bureau of Indian Standards, for measuring the efficiency of cookstoves (Funk, 2000).
- The Chinese standard Water Boiling Test, developed by the State Standards Organisation of the Peoples Republic of China, termed '*Testing Methods for the Heat Properties of Civil Firewood Stoves*' (Bokhary *et al.,* 2002).
- The comparative Water Boiling Test.[7]

2.4.3 Limitations and assumptions of the Water Boiling Test

Several procedures for conducting and analysing Water Boiling Tests for performance evaluation of fuel/stove combinations have been recommended since the early 1980's (Johnson *et al*., 2010; Makonese *et al*., 2010b; Rani *et al*., 1992; DNES, 1988; Krugmann, 1987). "*While the basic purpose is the same in all advocated procedures, there are certain procedural, computational…*" (Rani *et al*., 1992:922) and measurement related differences among them. Some studies have claimed that estimates of emissions using the standard Water Boiling Test are flawed since the method does not simulate real world uses of fuel/stove combinations (Roden *et al.,* 2009; Berrueta *et al.,* 2008; Johnson *et al.,* 2008). "*Emissions from cookstoves have largely been estimated using standardised Water Boiling Tests conducted in simulated kitchens (Smith et al., 2000b; Zhang et al., 2000). Since the WBT cannot replicate normal stove use in homes (Berrueta et al., 2008) especially in countries such as Mexico where the majority of cooking involves tasks that do not involve boiling of water (Dutt & Ravindranath, 1993), these estimates may not reflect emissions from homes during daily activities*." (Johnson *et al.,* 2008:1207). Reported discrepancies between modelled emissions estimates and measured atmospheric concentrations may be attributed in part to such biases in the Water Boiling Test method (Johnson *et al.,* 2008). The following section briefly examines some of the limitations of the WBT.

Estimation of thermal and emissions performance

"*In Mexico the relationship between using emission factors from* Inter-governmental Panel on Climate Change (IPCC), Water Boiling Tests *and normal daily stove use in homes were evaluated for both traditional open fire stoves and improved Patsari stoves.*" (Johnson *et al.,* 2007:11). Nominal combustion efficiency during Water Boiling Test in a "*...simulated kitchen was found to substantially over predict the efficiency of open fires".* Results from the "*…simulated kitchen indicated that the mud-cement Patsari was 7% less efficient than the traditional open fires, while the converse was true in homes during normal stove use by residents*." (Johnson *et al.,* 2007:11).

---

[7] This is an adaption by Jean-Francois Rozis of the test method and procedure of the international Water Boiling Test standard, modified to account for the real customs and habits of cooking in Cambodia.

Carbon dioxide, carbon monoxide, and NO_x emissions were monitored during single cooking events for wood burning open fires in rural homes (Kituyi *et al.,* 2001; Ludwig *et al.,* 2003) and the $CO:CO_2$ ratios were found to be over three times higher than those found by Smith *et al*. (2000b) and Zhang *et al*. (2000) for WBT in simulated kitchens using similar fuel/stove combinations. "*These lower combustion efficiencies during in-home stove use suggest the WBT may not provide an emissions test reflective of typical stove use, although simultaneous emission testing of in-home use and the WBT would be required to draw such conclusions*." (Johnson *et al.,* 2008:1207).

Such documented bias of the WBT calls for concerted efforts to develop more representative stove testing protocols: "*…the bias of the WBT in estimating combustion efficiencies during daily cooking activities is in opposite directions for the open fire and the Patsari…systematic adjustment for the bias is not possible between stove types…simple alteration of testing protocols of the WBT would be unlikely to produce representative emissions for both stove types, much less the extensive variety of fuel/stove combinations in use throughout the developing world*." (Johnson *et al.,* 2010:371).

"*From a climate modelling perspective, the combustion efficiencies of open fires appear to be overestimated using WBTs in simulated kitchens, resulting in an almost two-fold underestimation*" (Johnson *et al.,* 2008:1217) of products of incomplete combustion (PIC) per kg fuelwood burned. Using the WBT for cookstove greenhouse gas estimates in these communities could result in erroneous fuel use and emission levels. Hence, "*...emission factors derived from WBTs should be used with caution as input values in climate models. Rather, concerted efforts should be made to derive realistic emissions factors from*" (Johnson *et al.,* 2007:1217) representative models of real world uses of fuel/stove combinations.

Fire extinction

The Water Boiling Test assumes that extinction can be done through the removal of fuel supply, contrary to the batch-feeding design. In batch-feed devices, extinction involves tipping the stove to dump out large mass of hot bed of coals (Taylor, 2009). Depending on the amount of time it takes to extinguish the flames on the fuel and cool it down below the minimum pyrolysis temperature, significant errors in energy accounting from the amount of fuel actually used during the operating portion of the test may be created. Separation of char from unburned fuel is a time-intensive, error-prone, and potentially unsafe process in batch-fed devices, particularly those which use pellet fuels. The 'heat remaining in the fuel' necessary to determine the thermal efficiency, can be divided arbitrarily into moist pellets, dried pellets, torrefied and charcoaled portions. These portions can be aggregated into two arbitrary piles ('char' and 'fuel') with a heat value assigned to each. The 'fuel' fraction is assumed to be at its original moisture content (Pemberton-Pigott, 2010; personal communication). Recovery of these portions is not precisely defined in the protocols and is therefore dependent on the operator. It is impractical in field trials and most laboratory circumstances to determine what portions of a partially burnt pellets or wood sticks have been dried or pyrolised, and to assign representative residual heat content figures to them. The intrinsic error in this process, which forms part of the Water Boiling Test (WBT), is potentially large.

Fuel supply

The protocol assumes that fuel density, ash content and moisture content are consistent throughout the fuel supply. The protocol's assumption of fuel homogeneity extends to partially burned wood (Taylor, 2009). The procedure fails to account for the potential differences between burned fuel and fuel that has not been visibly charred but has lost most of its moisture. The protocol will likely underestimate the amount of energy left in the unburned fuel in batch-feed devices since large masses of moisture may have been lost from unburned fuel during the test. Thus, fuels to be tested have to be tested for moisture content and their calorific values determined before carrying out definitive tests rather than relying on tables of pre-determined calorific values.

Energy accounting errors

Energy accounting errors result from uncertainties in the calorific values of the fuels used. One error results from the assumption that everything that is labelled char during sorting is indeed char. Taylor (2009) argues that depending on the burn length and fuel chemistry, there can be significant amount of ash that is erroneously calculated as char. There are four stages through which the fuel progresses when wood burns (starting fuel, dried fuel, torrefied wood and charcoaled wood) but there is no way of separating the residue of any unburnt fuel into distinct components. The division along the continuum of the four stages, to which relevant heat values are applied, is somewhat arbitrary. In most cases the amount of heat remaining in the fuel is underestimated in the UCB WBT giving a lower assessment of the performance of the stove. This error significantly prejudices the performance of stoves that roast their fuel, when compared with equally performing stoves that burn sticks on the ends (Pemberton-Pigott, 2010; Personal Communication). Another error involves the test's assumption that char has a calorific value that is 1.5 times that of unburned fuel. The calorific value of char is influenced by fuel chemistry and the time-temperature exposure of the fuel. Chars that have been exposed to high temperatures have high calorific values compared to those that have been exposed to lower temperatures due to the increasing de-oxygenation of the fuel with exposure to heat (Taylor, 2009).

In spite of these documented problems associated with the Water Boiling Test, little research has focussed on the development of alternative testing protocols that can simulate real world uses of stoves.

2.4.4 Thermal efficiency and emissions performance metrics

Thermal efficiency

Efficiency is one of the common metrics taken from the Water Boiling Test. The test is supposed "*...to help stove designers understand how well energy is transferred from the fuel to the cooking pot*." (Bailis *et al*., 2007b:1). The thermal efficiency of a cooking device depends on how well the heat generated is transferred from the fuel to the pot (Olalusi & Bolaji, 2009). Ballard-Tremeer & Jawurek (1996) define efficiency as the ratio of energy entering the pot to the energy content of the fuel consumed. However, this measurement of energy transfer is incomplete, leading to a misrepresentation of thermal efficiency.[8] The "*...efficiency of a cooking process is thus difficult to define in technical terms*." (Ballard-Tremeer, 1997:130).

The time-averaged thermal efficiency of the pot/stove combination is reported as a percentage. The test calculates this as the ratio of enthalpy change of the water in the pot to the maximum theoretically available energy from combustion assuming no condensation of moisture in the product gases (Taylor, 2009). The energy transferred to the water is the sum of the latent heat, sensible heat, and the heat transferred away from the pot via convection, conduction, and radiation. This latter heat is not accounted for in the WBT calculation. During the simmering task, the stove function is to counterbalance these heat losses, but not to evaporate water from the pot. Yet, the evaporation of water, rather than the heat loss from the pot, is the only metric used. This mismatch between the measured quantity and the desired service occurs also during the *high* power water heating tests, but the impact is not as great (Pemberton-Pigott, 2010; personal communication).

The heat liberated from a fuel is done on a 'missing mass basis'. This result in a measurement error in some stoves/fireplaces that burn sticks progressively from one end, so that the amount of moisture evaporated from fuel not yet burned is small. A stove that entirely encloses a batch of fuel, tends to dry the whole batch during the initial phases (stove ignition), and then burn the dry wood and the char in the later phases. This means that for the latter batch type stoves, the energy per missing mass is low at the beginning of the combustion process but increases with time. For comparison between different fuel/stove combinations, there is need to measure the moisture content of the stack gases or the remaining fuel; this is still a technical challenge and stove evaluations often do not include this in the analysis of the results.

According to Baldwin (1987), stove performance is measured by its *percent heat utilised* (PHU), or by its *specific consumption* (SC). The definition of efficiency in Baldwin (1987) is similar to the

[8] Comment by Laura Fierce with the assistance of Crispin Pemberton-Pigott, on the online version 4.1.2 of the Berkley Water Boiling Test.

definition of PHU in the procedure of Rani *et al*. (1992). The PHU of a stove is "*...the percentage of heat released by the fire that is absorbed by the water in the pot*." (Rani *et al*., 1992:922). The SC is the total quantity of wood used for the simulated cooking process divided by the amount of water 'cooked'. The equation for the calculation of PHU is given by:

$$PHU = \frac{C_p M(\Delta T) + hfg\overline{M}}{M_f(LHV_f) - M_c(LHV_c)} \qquad \text{Equation 1}$$

where Cp is the specific thermal capacity of water, M is the mass of water in the main pot at the start, ΔT is the rise in water temperature in the main pot, hfg is the enthalpy of vaporisation, $\overline{M}$ is the mass of evaporated water, M_f is the mass of the fuel used, LHV_f is the lower heating value of the fuel, Mc is the mass of charcoal remaining, and LHV_c is the lower heating value of the remaining charcoal.

There are two notable omissions in the PHU equation given by Stewart (1987):

- The mass of water evaporated and the mass of water heated is measured for the main pot only (the second and subsequent pot(s) are ignored); and
- Water temperature fluctuations within each phase are ignored, that is, during the simmering phase the water temperature tends to fluctuate.

Baldwin (1987) recommends that the second and subsequent pots should be ignored in the calculation of efficiency (Ballard-Tremeer, 1997). Baldwin contends that "... *the additional heat recuperated by the second and subsequent pots increases the laboratory PHU, but is ineffective in actually cooking food because it is too low in temperature and because it cannot be easily controlled... the performance of multi-pot stoves in actual cooking of food is better predicted by their first pot PHU than by their total PHU.*" (Baldwin, 1987:92).

In calculating the thermal efficiency of a fuel/stove combination, the University of California Berkley Water Boiling Test 3.0 uses the following formula:

$$H_c = \frac{4.186 * (P_{ci} - P) * (T_{cf} - T_{ci}) + 2260(W_{cv})}{f_{cd} * (LHV)} \qquad \text{Equation 2}$$

In this calculation, the work done by heating water is determined by adding two quantities: (i) the product of the mass of water in the pot, ($P_{ci} - P$), the specific heat of water (4.186 J g^{-1} $^{o}C^{-1}$), and the change in water temperature ($T_{cf} - T_{ci}$); and (ii) the product of the amount of water evaporated from the pot and the latent heat of evaporation of water (2 260 J g^{-1}). The denominator is determined by taking the product of the dry-wood equivalent consumed during this phase of the test and the LHV (Bailis *et al.,* 2007b:25; Berrueta *et al.,* 2008).

The authors of the Water Boiling Test acknowledge that "*...direct calculation of thermal efficiency derived from the WBT is not a good indicator of the stove performance because it rewards the excess production of steam*." (Bailis *et al*., 2007b:2). This ratio indicated in the PHU is not entirely related to the task. For example, the 'loss' of energy by evaporation is used as a partial measure of the energy transferred to the pot, not as 'lost heat' (Ballard-Tremeer, 1997). "*Under normal cooking conditions, excess steam production wastes energy because it represents energy that is not transferred to the food. Temperatures within the cooking pot do not rise above the boiling point of water regardless of how much steam is produced*." (Bailis *et al.,* 2007b:2). This calculation makes an assumption that all fuel is burned to ash and that no charcoal is formed at the end of the burn cycle. Although the test was primarily developed for wood-burning stoves only (Bailis *et al.,* 2007b), the equation given for the calculation of thermal efficiency is typical for liquid fuels were no ash is formed at the end of the burn cycle.

Improved calculations of thermal efficiency need to be pursued and verified, particularly if they can be accomplished without a change in protocol. Thermal efficiency measures should be viewed with caution, mainly from the simmering test. A better measure is the quantity of fuel required to complete a task, known as specific consumption (Baldwin, 1987). Ballard Tremeer (1997) advocate for slight changes in the calculation of the PHU with regards to multi-pot stoves. He used the following equation for the determination of thermal efficiency (ŋ) of a multi-pot fuel/stove combination:

$$\eta = \sum_{k}^{K} \left[\frac{C_p M_k \left(\sum_{i=1}^{n} \Delta T \right) + hfg\overline{M_k}}{M_f \left(h^o f \right) - M_c \left(h^o c \right)} \right]$$

Equation 3

In this calculation K is the number of pots, k is the pot number, n is the final heating stage, I is the heating stage number, C_p is the specific thermal capacity of water, M_k is the mass of water in the pot k at the start, ΔT is the rise in water temperature in pot k, hfg is the enthalpy of vaporisation, $\overline{M_k}$ is the mass of evaporated water, M_f is the mass of the fuel used, h^of is the enthalpy of fuel combustion, M_c is the mass of charcoal remaining, and h^oc is the enthalpy of charcoal combustion.

Emission performance

There are different emission factors and quantification methodologies used around for the evaluation of pollution sources. These emission estimates are "*...important for developing emission control strategies; determining applicability of permitting and control programmes; ascertaining the effects of sources and appropriate mitigation strategies; and a number of other related applications by an array of users including federal, state, and local agencies, consultants, and industry*." (Karademir, 2006:1894).

An emission factor (E_m) for a pollutant can be defined as the mass of emitted pollutant per unit mass of fuel burned (Zhang *et al.,* 2000) or per defined task performed (Mitra *et al.,* 2002). "*It is a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant*." (Karademir, 2006:1894). In stove analysis, an emissions factor is a term given to a gas concentration that has been normalised for any dilution by excess air. It can be *mass based* or *task based*. Hildemann *et al*. (1991) refers to task based emission factors as emission rates. Mass based emission factors, on the other hand, can be used readily for the development of emission inventories where the amount of fuel used is available.

For fuel consumption, published emission factors based on fuel energy content are more accurate than those based on mass or volume, except when mass-based or volume-based factors have been measured at a source-specific level (EPA, 2005). In a study carried out by Zhang *et al*. (1999) on emission factors for 56 fuel/stove combinations in China and India, a *carbon balance* approach was used for the determination of the emission factors and were reported in grammes of pollutant per kilogramme of fuel consumed ($g\ kg^{-1}$). Because air flow rates vary greatly in actual homes, Zhang *et al*. (1999) applied a carbon balance approach to measure emission factors. "*This approach does not require the measurement of air flow rate but requires a complete carbon analysis in the fuel, ash and unburned residues, and all airborne emissions*." (Zhang *et al*., 1999:354). Since different amounts of fuel are needed for the same cooking task for each fuel/stove combination, task based emission factors rather than the fuel mass based are a better performance index to compare the pollution potential of different fuel/stove combinations (Zhang *et al*., 1999; Zhang & Smith, 1996; Joshi *et al*., 1989). The simplest task measure is the release per unit energy delivered to the pot ($g\ kJ^{-1}$) (Zhang *et al*., 1999).

If the emission rate and the fuel burn rate for a combustion source are both constants, the emission rate would be the product of the emission factor and the burn rate. The emission rate, fuel mass based emission factors and task based emission factors can be inter-converted if the necessary parameters are known (Mitra *et al.,* 2002). Zhang *et al*. (2000:4541) contends that: "…*emission factor per delivered energy, rather than per cooking task as used conventionally, is more appropriate to use for the comparison of emissions among different stove*".

The relationship between a mass-based emission factor (E_m) and the task-based emission factor (E_e) in domestic stoves or boilers can be described mathematically. The conversion from emissions per kg of fuel to emissions per MJ delivered energy can be achieved using the following equation:

$$E_e = \frac{E_m}{H.\eta} \qquad \text{Equation 4}$$

where H is the fuel energy content or calorific value ($MJ\ kg^{-1}$) and η is the thermal efficiency (%) of the stove (Zhang *et al.,* 2000:4541).

Emission masses per task relate directly to human exposure and are calculated as follows:

$$M_E = \left[\int_{t=0}^{T} C_M v_{flue} dt \right] \qquad \text{Equation 5}$$

where M_E is the mass of the pollutant (g), T is the test duration (s), C_M is the pollutant concentration (g m^{-3}) at time t and v_{flue} is the flue extraction rate (m^3 s^{-1}) (Ballard-Tremeer, 1997).

From this calculation, emission factors, defined as the ratio of the mass of pollutant to the mass of fuel burned, can be calculated. Emission factors can be calculated using the equation used, for example, by Macumber & Jaasma (1982):

$$E = \frac{M_E}{M_f - M_c} \qquad \text{Equation 6}$$

where ($M_f - M_c$) is the mass of the fuel burned.

This emission factor is not exactly the same as the emission factor used by some researchers (Joshi *et al.,* 1991; Joshi *et al.,* 1989; Ahuja *et al.,* 1987) where the denominator $M_f - \frac{h^o c}{h^o f} M_c$ is used (Ballard-Tremeer, 1997). However, "*...to relate the emission of a pollutant to the 'equivalent wood consumed' defined according to the enthalpy of combustion of the fuel and char is deceptive from a mass balance perspective and would lead to higher factors - generally about 25%.*" (Ballard-Tremeer, 1997:43).

The Water Boiling Test (WBT) (Bailis *et al.,* 2007b) calculates emission factors per task accomplished, which is not very useful unless everyone performs the same task. This is not revealing if it is done only once during the whole test. A possible problem with the *carbon balance* model is that the *CO_2 max* for a fuel (maximum possible concentration in the stack) is not usually known with reasonable precision. "*During combustion, most of the carbon becomes CO and CO_2, and neglecting the other carbon species (methane, non-methane hydrocarbons, and carbonaceous aerosols) may introduce an error of 1-4%. Therefore, emitted CO_2 and CO can serve as a proxy for the fuel combusted, when adjusted for the carbon fraction of the fuel and for the ambient background. Thus the ratio between pollutant and carbon as CO and CO_2 is an approximate emission factor*." (Roden *et al*., 2006:6752).

The results need to be presented in a way that allows for comparison between fuel/stove combinations. An alternative approach to the carbon balance is the *oxygen mass balance* model. The method requires taking the chemistry of the stack gases into consideration to determine what the actual level of excess air in the stack is. The approach is to measure the total oxygen content in the air stream and correct it to zero excess air by measuring the residual oxygen in the air stream (Makonese *et al*., 2010c). This method is further discussed in section 3.3.7.

2.5 Variants in Stove Testing Methods

There are a variety of testing methods of stove performance, all variants of the Water Boiling Test (VITA, 1985), which have been used in previous studies for performance evaluation of diverse fuel/stove combinations. Various procedural differences exist among these test methods. The following section examines in brief other efforts in stove testing since the development of the VITA stove testing standard.

2.5.1 The Wood-burning Stove Group (WSG)

The work of the Wood-burning Stove Group (WSG), University of Eindhoven, revealed that reliable and comparable experimental data are only obtained when stoves are tested according to a fixed test scheme. The need for standardisation became apparent after a series of field tests. The VITA (1985) Water Boiling Test experimental set-up and procedures were altered (Bussmann *et al.,* 1983; Bussmann *et al.,* 1985) as part of the WGS procedure to give highly reproducible results. The WSG aimed at establishing standard test procedures by eliminating all variables in the stove testing not directly related to construction (Bussmann, 1988; Claus *et al.,* 1982). Bussmann (1988) argues that this strained the relationship between laboratory testing and actual cooking, blocking any communication between the two ever since. The WSG method entails testing the stove using five litres of water in a 280 mm diameter and 240 mm deep pot, raised 130 mm above the fuel-bed. The tests are carried out with a lid on. The weight of the fuel is measured every 10 seconds. However, the WSG method is prescriptive in the fuel type, fuel size and fuel load used - *white fir* (species name not specified) wood, oven dried at 150°C for up to 48 hrs is cut into 20x20x67 mm^3 pieces averaging 100 g each. The total fuel quantity used in the experiment is divided into equal parts of 100 g each and the stove is charged at time intervals determined by the desired fire-power. The test lasts for one hour and the procedure reports only one figure of merit – the efficiency of the fuel/stove combination (Rani *et al*., 1992).

2.5.2 The Biomass Technology Group (BTG)

The Biomass Technology Group (BTG) located in Enschede, Netherlands developed an alternative method to the WBT. The method is reported to closely follow the VITA (1985) standard, but is better adapted to laboratory and field conditions. The procedures cater for four tests: a *simple* Water Boiling Test; an *extensive* Water Boiling Test; a fuel consumption test; and a controlled cooking test.

With the simple WBT, essential characteristics of a stove are determined: maximum power, efficiency at maximum power, minimum power, and efficiency at minimum power. At maximum power water is brought to a quick boil and kept boiling for 30 minutes. For this and other tests the procedure specifies that the pot lid should *not* be used. The maximum power phase is directly followed by the minimum power phase where the water is kept simmering for 60 minutes. At the beginning and end of both phases fuel and water are weighed and temperatures are measured.

The regimen of the *extensive* WBT is the same with that of the simple WBT except that all measurements are done every five minutes and gas analysis can be added. Calculations are done every five minutes to give a detailed picture of stove behaviour at different phases of the fire. In the fuel consumption tests, water is brought to the boil and kept simmering for 60 minutes, simulating a cooking session. The only parameter measured for this task is fuel consumption.

The BTG procedures, however, do not provide for testing the stove across a full range of power settings. As pot lids are not used in the tests, what is normally referred to as *low* power setting in most test methods may actually be a power setting close to the *medium* power setting or between the *medium* power setting and the *high* power setting. This is because it may be impossible to maintain the temperature of water between three degrees below and boiling temperature for 60 minutes using the lowest sustainable power setting.

2.5.3 The DNES India proposed Water Boiling Test

The Department of Non-conventional Energy Sources (DNES) India test method is planned for two hours. The method does not provide a motivation for planning the stove test for two hours. "*Fuelwood is stacked in small equal lots in sufficient quantity so as to last for the entire test duration*." (Rani *et al*., 1992:922). The method of calculating thermal efficiency is the same as that suggested by Bailis *et al*. (2007b). The procedure is reported to involve use of approximately "*...2 kg of wood cut into pieces 100-150 mm long and 30 - 40 mm in diameter. These are taken and divided into eight equal batches of 250 g each. The stove is charged at a rate of 250 g every 15 minutes so that test lasts for 2 hours. The pot is weighed empty, filled with water to two-thirds capacity and re-weighed again*." (Rani *et al*., 1992:922). This procedure does not report on the size of the pot used. The fire is lit and the pot of water with a lid on is brought to a quick boil. On reaching boiling, "*…the lid is taken off and testing is continued for*" the remainder of the time. At the end of the test, "*...the pot with water is weighed and any charcoal left is also weighed*." (Rani *et al*., 1992:922). These values are then used in the calculation of thermal efficiency, specific fuel consumption and firepower of the stove.

2.5.4 Bois de Feu (France) Water Boiling Test

The *Bois de Feu* test procedure recommends the Water Boiling Test to be conducted in two phases: a *high* power and a *low* power phase. The procedure is almost identical to that suggested by VITA (1985) with the exception that charcoal is not put back into the stove after the *high* power phase (Rani *et al*., 1992). The method uses mass of water left after *high* power phase for calculation of thermal efficiency. This is at variance with the procedure suggested by VITA (1985) which uses initial amount of water. The procedure specifies that the pot lid should not be used for the entire duration of the experiment.

There are other variants to the Water Boiling Test used by different scholars and institutions, some of which are summarised in Table 1.

Table 1: Differences in stove testing procedures in use

Refs	Ignition	Refuelling	Task	Control	End Point
VITA **(1985)**	As normally done in households of the area	As required	Heat water 2/3 pot capacity to boil as rapidly as possible, simmer 30 minutes	As required	30 minutes after boiling.
SABS 1403 (1986)	30 minute ignition period before test begins	*	6 hour heating period	*	*
PD 6434 (1969)	As recommended by appliance manufacturer	As recommended by appliance manufacturer	Steady state operation at rated output	Pre-set controls are not adjusted unless manufacturer states that adjustments are necessary	Dependant on appliance and Manufacturer advice
BS 3841 (1972)	Ignition gas at set rate, fire must reach 1.17 KW in 50 minutes for valid test. Defined fuel charge for ignition.	Refuelled when power output drops below defined level. 20 sec before and after refuelling emission measurements is reduced.	Three or four refuel charges	Preliminary tests are used to set controls which then remain unchanged for the duration of the test	Power drops below defined level after third or fourth radiation peak.
McCrillis & Burnet (1990)	Newspaper and kindling, refuelled after 10 minutes	Refuelled as necessary to maintain desired burn rate	Predetermined time with fire maintained at desired burn rate	*	Test completed after 8 hrs
Smith *et al* (1993), Smith (1992)	*	Single charge, no refuelling	Heating 2 litres of water	*	30 minute duration
Butcher *et al*. (1984)	Small amount of kerosene for kindling	Fuel added when necessary	Heating 2 litres of water, boiling for 15 minutes and simmer for 30 minutes	Rearranged and blown with a blow pipe as needed	30 minutes after boiling, end of simmering
Nangale (1992)	*	One charge of fuel, no refuelling	Heat water with pot with lid. Pollutant monitors started when steady flame established	Minimal fire tending	End point when temperature of water started dropping steadily

Refs	Ignition	Refuelling	Task	Control	End Point
Islam & Smith (1989)	*	Single charge	*	Controls unchanged	*
Ahuja *et al* (1987), Joshi *et al.*, (1989), Joshi *et al*. (1991)	End of each piece of wood dipped in a measured amount of kerosene	Single charge of fuel, no refuelling	3.5 litres of water heated in pots with lids, and maintain boiling for 15 minutes	Fire tended to ensure a steady flame	Fire removed from room when water temperature dropped by 0.5°C (about 15 minutes after boiling)
Berrueta *et al*. (2008)	*	*	3 litres of water, high power cold start, hot start and simmering for 45 minutes. 3 repetition for each fire/stove type	Fire tended	End test after 45 minutes of simmering
Boy *et al*. (2000)	According to appliance manufacturers	5-7 kg of fuel, refuelling as necessary	6.5 litres, 2.4 litres and 1.6 litres water boiled at high power for 15 minutes, simmering for 60m minutes	Fire tended to ensure a steady flame.	End test after 60 minutes of simmering

* Not specified

Source: Based on Ballard-Tremeer (1997); supplemented by own survey post-1998.

2.6 Performance of Paraffin Stoves and Related Issues

In South Africa, among the Black urban population, households are reliant on paraffin as a cooking and space heating fuel (Roberts & Wentzel, 2006; Muller *et al*., 2003; De Wet *et al*., 2001). Even though several African countries advocate for the use of liquefied petroleum gas (LPG) rather than paraffin as a preferred urban cooking fuel, it is not the most economic solution. Paraffin offers, in many cases, the least-cost solution for household cooking in many countries. However, it has been associated with many problems ranging from paraffin poisoning, indoor air pollution to property loss due to shack fires (www.pasasa.org).

The hood method in conjunction with the Water Boiling Test (WBT) has been used in the performance evaluation of paraffin stoves. Tschinkel & Tschinkel carried out Water Boiling Tests on four types of stoves: pressure fed paraffin burner; wick fed paraffin burner with fixed wick; variable wick paraffin burner; and a propane burner. In the tests they used small pots with casserole shapes (1 litre and 2 litre capacity) (Tschinkel & Tschinkel, 1975). The results they obtained are summarised in Table 2. The range of efficiencies corresponds to the range of power settings.

Table 2: Comparison of efficiencies of three paraffin stoves and one gas stove

Stove Type	Pmax (KW)	Pmax/Pmin	Efficiency Range (%)
Pressure fed Paraffin burner	2.55	3.14	47 - 56
Variable wick paraffin burner	0.99	1.09	38 - 41
Fixed wick paraffin burner	2.18	1.35	31 - 38
Propane burner	1.64	4.4	47 - 61

Source: Tschinkel & Tschinkel (1975)

The variability in the results of wick based paraffin stoves and pressurised paraffin stoves in Tschinkel & Tschinkel's work may be attributed to a lack of standardisation of the test procedure and the inadequate appreciation of the different factors that determine the efficiency of a stove (Prasad *et al.,* 1983).

Islam (1980) carried out tests on paraffin fuelled wick stoves in rural Bangladesh. He used several pots of different shapes, sizes and materials, and two types of liquid fuels (paraffin and methanol). In most of his work Islam (1980) indicated the power settings of the fire. Prasad *et al*. (1983) contends that in Islam's report some of the pot dimensions are not explicitly indicated and therefore are not easy to figure out from the tabulated information. Reported efficiencies of 53% to 54% were attributed to the use of 5.5 kg of water in a pot of 280 mm diameter, with a spherical bottom (Prasad *et al.,* 1983).

A study on rural energy in Fiji reported experimental results of several types of cookstoves (including the Hong Kong 10-wick stove and the Primus No. 1) evaluated for performance using a Water Boiling Test procedure plus an additional test of heating water from ambient to 60ºC (Siwatibau, 1981). Efficiencies were averaged: one obtained by heating water from ambient temperature to 60ºC and the other obtained by heating the water from ambient temperature to 100°C.[9] The test results were compared to those obtained by the New Zealand Consumer Council (NZCC) (Table 3). The NZCC efficiencies were stated to have been obtained by heating two litres of water from ambient temperature to boiling. In both tests, reference was not made to the power settings or pot sizes used to obtain these results (Prasad *et al.,* 1983).

Table 3: Comparison of paraffin stove test results of Siwatibau and NZCC

Stove Type	Thermal Efficiencies (%)	
	Siwatibau (1981)	NZCC
Primus No. 1	15 – 29	37.7
Hong Kong Wick	30 – 57	27.5

Source: Prasad *et al*. **(**1983)

[9] This does not seem to be a plausible way of averaging efficiencies of fuel/stove combinations since the stove is performing two different tasks (i.e. boiling and heating water to 60ºC).

Lloyd & Visagie (2007) used the Water Boiling Test to evaluate the performance of gel fuelled appliances and compared them to alternative cooking fuels such as paraffin. A measured amount of water (1.5 L) was used and the water heated from a temperature of 20ºC to boiling. The test did not include a simmering phase. The initial phase of the test involved a high power boil. On reaching boiling the test was stopped and results analysed. The combustion products were collected in a hood and a combustion analyser was used to analyse the $CO:CO_2$ ratio and the level of unburned hydrocarbons. Tests were run on *high* and *low* power settings respectively to determine different fuel/stove emissions and thermal performances. The combustion efficiencies of paraffin wick stoves were reported to be above 10 % at the *low* and *high* power settings (Lloyd & Visagie, 2007). The reported results may not be indicative of the actual performance of the stoves since only a single pot size with a specified volume of water was used for the tests.

2.7 Domestic Coal Combustion and Related Technologies

In a study carried out by Smith (2002), source contributions to quantifiable particulate emissions in the city of Johannesburg were reported to be 48% attributable to domestic coal burning, 22% to scheduled processes, 20% to vehicle-tailpipe emissions, and 10% to tailings impoundments. It is estimated that 3.3 million tonnes of coal are consumed by the household sector of the economy (DME, 2004). This represents about 3% of the annual coal utilisation. This however contributes to approximately 30% of the average national particulate matter contribution to the atmosphere (Nuwarinda, 2007).

A source apportionment study carried out in Soweto Township showed that domestic coal combustion contributed approximately 70% of the ambient total particulate matter (Annegarn & Sithole, 1999), while a similar study in the Vaal Triangle indicated that the combustion of coal contributed on average 37% of the ambient total particulate matter in summer with highs of about 65% in winter (Engelbrecht *et al.,* 1999, Terblanche *et al.,* 1994). Household coal combustion is considered to be the greatest emission source of black carbon (BC) and an important source of organic carbon (OC) in China (Chen *et al.,* 2009). However, the type and grade of coal matters in this regard as reported by Chen *et al*. (2009:9497), "*…if medium volatile bituminous coal (MVB) is prohibited as a household fuel together with the promotion of briquettes, BC and OC emissions in this sector will be reduced by 80% and 34% respectively.*"

2.7.1 Health risks due to exposure to smoke particles from coal

Particulates are small discrete masses of solid/liquid matter that remain individually dispersed in gas or liquid emissions. Atmospheric particulate matter (PM) "*...is a complex mixture of airborne particles and liquid droplets composed of acids (such as nitrates and sulphates), ammonium, water, black carbon, organic chemicals, metals and soil (crustal) material.*" (Nussbaumer *et al.,* 2008:5).

PM can be divided into three size fractions: Total Suspended Particles (TSP), PM_{10} (aerodynamic diameter <10 μm), and $PM_{2.5}$ (aerodynamic diameter <2.5 μm).

Particulate matter poses a significant influence on the climate due to their interaction with incoming light and outgoing infrared radiation. Particles in the atmosphere scatter incoming light and absorb the outgoing infrared radiation. The net effect on the surface temperature depends on the complex interactions of energy absorption and transfer (Mitra *et al.,* 2002). Particle size is the main determinant of health effects (Nussbaumer *et al.,* 2008). PM_{10} was previously the major indicator of health relevance of in ambient particulate air pollution. However, $PM_{2.5}$ has the greatest adverse health effects because these smaller particles can pass through the bronchi to the bronchioles and settle in the alveolar region of the lungs. PM_{10} are coarser than $PM_{2.5}$ and can be trapped by nasal cilia (hairs), or be impacted in the upper bronchial tubes. The size and the density affect the retention time and travel distances in the atmosphere. $PM_{2.5}$ has a long residence time due to lower gravitational setting velocity (WHO, 2006). PM_{10} tend to settle down due to gravity within hours.

Long exposure to particulate matter can cause serious health problems. "*Each 10 µg m^{-3} elevation in fine particulate air pollution was associated with approximately a 4%, 6%, and 8% increased risk of all-cause, cardiopulmonary, and lung cancer mortality, respectively*." (Pope *et al.,* 2002:1132). However, Pope *et al*. (2002) reported that measures of coarse particles were not consistently associated with mortality. WHO (2006) has published a guideline based on health effects with limiting values for PM_{10} and $PM_{2.5}$ for both short-term and long-term exposures. Because of the World Health Organisation's air quality guidelines the South African Government (Government Gazette, 2009), and the "*...the European Commission, United States Environmental Protection Agency (USEPA) have used the approach to revise their air quality standards for particulate matter*." (Nussbaumer *et al.,* 2008:6).

2.7.2 Basa njengo Magogo - BnM (Top lit up-draft method) and the classical fire-lighting method (Bottom lit up-draft method)

There are two lighting methods used for lighting a coal fire in an *imbaula* (the traditional or conventional fire lighting method and the *Basa njengo Magogo - BnM* method). In the classical fire lighting method (conventional method), semi volatile emissions from the heated coal rise through the cold zone and condenses into droplets before escaping into the atmosphere. Consequently, the smoke that is emitted from this type of fire is not burnt. Hence, the method gives out a lot of smoke during the ignition stages through to pyrolysis. In the *Basa njengo Magogo* method, the hydrocarbons produced pass through the hot flame zone with enough supply of oxygen to allow for complete combustion. This ensures that the hydrocarbons are burnt resulting in a significant reduction in visible smoke and particulates. The *Basa njengo Magogo* method burns longer for the same amount of coal and has been shown to use approximately 20% less fuel compared to the conventional method (DME, 2004; Le Roux *et al.*, 2009).

Figure 1 shows differences in the arrangement of the fire between a classical fire lighting method and the *Basa njengo Magogo*.

The Department of Minerals and Energy's low-smoke fuels programme showed that low-smoke fuels had a role to play in reducing air pollution to acceptable levels. This led to the formation of an *Integrated Household Clean Energy Strategy* (IHCES) which incorporates measures such as the *Basa njengo Magogo* (BnM) (DME, 2004).

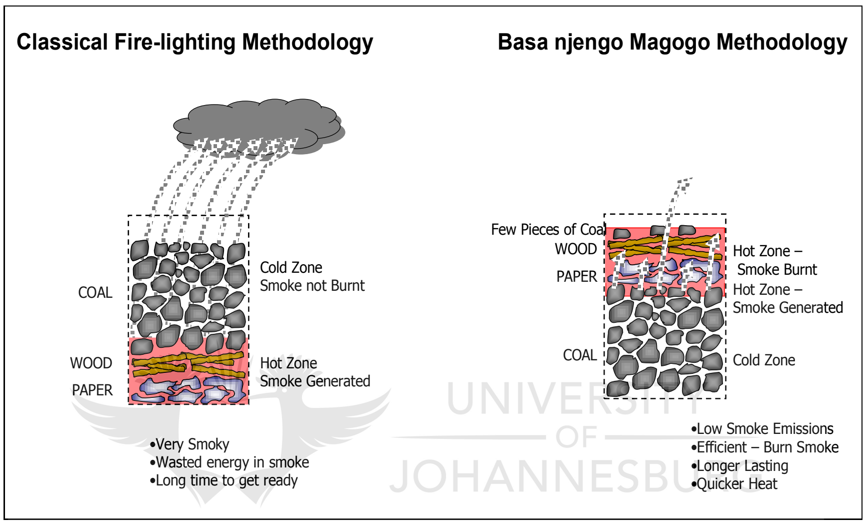


Figure 1: Differences between the classical fire lighting method (BLUD) and the Basa njengo Magogo (TLUD) method

Source: Department of Minerals and Energy (2004)

The *BnM* method holds a potential, not only to reduce air pollution but to result in coal and monetary savings for low-income households. It has been successfully demonstrated to over 80 000 households in coal burning areas of South Africa (Balmer, 2007). Since the method can potentially reduce ambient air pollution caused by the use of household coal in a relatively short period by approximately 80% (Trade and Industry Chamber, 2004), it represents the highest impact on health from a benefit-cost and employment point of view. The method is a low cost option with a great potential for reducing smoke caused by the burning of coal as it does not require changes in the fuel or corresponding devices used but a change in user behaviour (PDC, 2004). Work done by Nova in eMbalenhle indicated a 60% reduction in smoke compared with the conventional method of bottom-lit ignition (Le Roux *et al.*, 2009).

2.7.3 Domestic coal combustion technologies

While it can be argued that all coal fires are gas fires, the term 'gasifier' refers to a stove designed to generate coal gas, cook with it and leave at least some coke at the end. It is possible to build a coke gasifier, however, it is common to think of a gasifier as a stove that creates and burns only the volatiles in a fuel (Pemberton-Pigott *et al.,* 2009).

Research in coal gasification has progressed much further than research in wood gasification (Saravanakumar *et al.,* 2005). Studies undertaken in the past focussed on updraft gasification stoves using small wood pieces as feed (Khummongkol & Arunlaksadamrong, 1990; Kayal *et al.,* 1994; Bhattacharya *et al.,* 1999; Saravanakumar & Haridasan, 2002). However, up to date there is no commercially available coal burning device (downdraft stoves) suited to township cooking (Pemberton-Pigott *et al.,* 2009).

Gasifiers are known to have limitations and some of the disadvantages are as follows:

- more complex to operate; can produce noxious fumes when things go wrong,
- not yet well engineered for small scale applications; large ones are well known as they supply 'coal gas' in piped gas systems,
- may produce large quantities of unwanted coke, obliging the cook to purchase more fuel,
- difficult to change the power setting while yielding quality gas (Pemberton-Pigott *et al.,* 2009).

The Sardar Patel Renewable Energy Research Institute (SPRERI) developed the *invented downdraft gasifier* cookstove. "*It operates using natural convection of air. A major advantage of the inverted downdraft gasifier is that the rate of gas production depends on the amount of primary air admitted at the bottom. For this reason a tight sealing valve was put on the bottom which permits a wide range of air adjustments*." (Panwar, 2010:311). The inverted down draft gasifier stove called 'wood gas stove' has the potential to replace LPG stoves since the combustion of the gaseous mixture of CO and H_2 can be complete, thus minimising the emissions of products of incomplete combustion (PIC), which is a major problem with solid fuel combustion (Belonio, 1993). The CO_2 emissions in the SPRERI gasifier stove was reported to be in the range 22-26 ppm and CO emissions in the range 3-6 ppm. Both emissions were within the safe limits as quoted on indoor air quality fact sheet.[10]

[10] Indoor air quality: http://store.cleanair4life.com/PDF/IndoorAirQuality_AirQualTestKits.pdf. (Accessed 25 Nov 2009)

2.7.4 *The bottom-lit down-draft stoves*

The Sustainable Energy Technologies and Research (SeTAR) Centre, situated at the University of Johannesburg, has been involved in the design and development of bottom-lit down-draft (BLDD) coal stoves. The first SeTAR BLDD prototype was an attempt to build a space heater. Components of the first device (a basic space heater) included a fuel chamber, combustion chamber, a 230 mm cube body and a 75 mm diameter chimney. The grate was made from high temperature element wire which can operate at 1 300°C (Pemberton-Pigott *et al*., 2009).

The BLDD is able to maintain a flame projecting downward below the grate because the ash keeps falling away exposing the burning coke. Tests run at New Dawn Engineering[11] in 2004 showed that the ash formed at the burning face of the grate of a BLDD coal stove fall naturally downward as the coke is combusted. Principally, the BLDD uses gravity and the draft to get rid of the ash (Pemberton-Pigott *et al.,* 2009). Gases are drawn downward through the coke bed. The volatile and semi-volatile hydrocarbons that are produced from the solid coal during pyrolysis are efficiently combusted in the coke bed. Thus, the major source of particulate matter from domestic coal burning is eliminated (Pemberton-Pigott, 2010; personal communication).

2.8 Charcoal Combustion in the Developing World

Charcoal is the solid residue from the process of heating wood in the absence of oxygen - charring. The manufacturing process of charcoal separates and eliminates most of the particulates and other hydrocarbon emissions, but never eliminates carbon monoxide. Hence CO emission factors for charcoal are relatively high compared to fuel-wood (Smith, 1987). Charcoal-making kilns vary greatly in structure and size, and have variable air supply controlling mechanisms. The carbonisation process for charcoal making is an inefficient process due to the use of wet wood, poor stacking methods, less process control, and not using a chimney to force inverted draft (van der Plas, 1995). The products of incomplete combustion emitted during the charcoal-making process include carbon monoxide, methane, other volatile and semi-volatile organic compounds and particulate matter (Pennise *et al*., 2001). The idea behind charcoal production is to drive off all volatile components and these condense to form visible smoke. The semi-volatile matter in charcoal comprises of all those liquid and tarry residues not fully driven off during the carbonisation process. Combustion of these gases provides the heat in the kiln. If the carbonisation process is prolonged at high temperatures, then the content of the volatiles is low. Consequently, when the carbonisation temperature is low and time in the kiln is short, then the volatiles increase. High volatile charcoal is easier to ignite but may burn with a smoky flame. Low volatile charcoal is difficult to light but burns cleanly (FAO, 1987). Due to its low moisture and high carbon content,

[11] New Dawn Engineering, Matsapha, Swaziland. < www.newdawnengineering.com>

charcoal contains large amounts of energy per unit mass (give range) compared to the original wood (give range) (Tshikalanke, 2007). Charcoal produces less smoke because of low volatiles and is more compact to burn on a fire compared to wood.

Charcoal is mainly an urban phenomenon in Africa (Tshikalanke, 2007:10). Studies indicated that charcoal is used to a greater extent than wood in urban areas of Africa (Kituyi *et al.,* 2001; Marufu *et al.,* 1999). Charcoal, as an alternative to other cooking fuels, has twice the energy content of wood and this is one of the principal attractions for suppliers and consumers (Foley, 1986). Transportation of wood from the forest to consumers in urban areas is cost intensive (i.e. high cost per unit mass) and therefore wood is often replaced by charcoal, which is easy to transport (Andreae, 1991). It is argued that the higher consumption of charcoal in urban areas is mainly due to the convenience associated with its usage and cost. In rural areas, there is abundant fuelwood close to source, and hence no compulsion to use charcoal which is higher in cost of labour or cash. However, the use of charcoal as a household fuel is small, not exceeding than 9% for any income group, and contributing to about 1% of total household fuel use (Behrens, 1986).

Most of the specifications used to control charcoal quality have originated in the steel and chemical industry (Foley, 1986). Buyers tend to make use of these industrial quality specifications even if the targeted markets are domestic or barbecue markets (FAO, 1987). The main use of charcoal in households of the developing world is for space heating and cooking food. Unlike fuelwood, charcoal transfers a good deal of its heat to the cooking vessel by radiation from the glowing bed of fuel. Burning fuelwood, where hot gases are produced by long lazy flames, transfers the heat to the cooking vessel by convection. For heat transfer by convection, the hot gas must contact the cooking vessel for the heat to be transferred, but radiant heat is transferred by infrared radiation emitted directly from the fuel bed and absorbed by the surface of the cooking vessel.

Combustion of charcoal can either take place either in the gas phase or once volatiles are removed combustion can take place on the surface of the solid fuel. Charcoal reacts with oxygen to form colourless carbon monoxide gas, which then burns with a faint blue flame with more oxygen from the air to produce carbon dioxide gas. The limiting factor in this process is the diffusion of oxygen to the surface of the fuel. Due to the exothermic nature of these reactions, charcoal reaches a glowing red and radiates heat energy and the hot carbon dioxide gas leaves the combustion zone giving up its heat energy to the cooking vessel through convection. The gas temperature falls as it transfers heat and passes off into the room. After the charcoal has burned, what remains is ash, consisting of mineral matter (SiO_2) (Bussmann, 1988). It is important to note that in a fire these processes occur more or less simultaneously although at different locations. Charcoal combustion is relatively clean and odourless compared to fuelwood or coal. As a result of this clean burn, charcoal stoves are normally designed and fabricated without flues.

2.8.1 Health effects of charcoal use

Bautista *et al*. (2009) investigated the effect of charcoal smoke exposure on risks of acute upper and lower respiratory infection (AURI and ALRI) among children under the age of 18 months in Santo Domingo, Dominican Republic (1991–1992). "*Children living in households using charcoal for cooking were age-matched to children living in households using propane gas and were followed for one year. Fuel use and new episodes of AURI and ALRI were ascertained fortnightly through interviews and medical examinations. Household indoor air concentration of respirable particulate matter (RPM) was measured in a sample of follow-up visits. Incidences of AURI and ALRI were reported to be 4.4 and 1.4 episodes/child-year, respectively*." (Bautista *et al*., 2009:572). They concluded that exposure to charcoal smoke increases the risk of acute lower respiratory infection (ALRI) in young children, an effect that is probably mediated by respirable particulate matter (RPM) (Bautista *et al.,* 2009; Devine *et al.,* 2002). Ezzati & Kammen (2002) and Murray & Lopez (1996) reported that a transition from burning fuelwood in a three-stone fire to charcoal can reduce PM_{10} exposure of household users by 75-95%, resulting in a 45% reduction in childhood lower respiratory infections.

A study carried out in Mozambique by Ellegard (1996) examining the association between exposure to cooking fuel emissions and health in Maputo reported that there were no differences in cough symptoms between charcoal and modern fuel users. However, the study reported that wood users were exposed to significantly higher levels of particulate emissions, including black carbon, than users of charcoal or modern fuels (Table 4). Particulate emissions from charcoal are lower than those from fuelwood and coal. Therefore, charcoal is an attractive option from a black carbon (BC) reduction perspective.

Table 4: Concentrations of particulates measured while cooking with different fuels

Fuel Type	Mean Particulate Concentration (µg m^{-3})
Wood	1200
Charcoal	540
LPG	200
Kerosene (Paraffin)	760
Coal	940

Source: Ellegard (1996).

Charcoal emissions are less irritating compared to fuelwood smoke but contain higher levels of carbon monoxide. Since carbon monoxide (CO) cannot be detected by human senses, indoor levels of the gas can rise to lethal levels without the corresponding warning signs such as irritation and cough that would be created from fuelwood smoke. Therefore, charcoal could be responsible for more acute CO poisoning than other biofuels (Wallenstein, 2003).

2.8.2 *Performance of selected charcoal stoves*

Performance evaluations of charcoal stoves were carried out by Jetter & Kariher (2009) on the UCODEA and Lakech stoves. Both the Urban Community Development Association (UCODEA) and the Lakech stoves have a metal body with a ceramic liner and grate to hold the hot charcoal. Ventilation is controlled by adjustable vents on the bottom of the stoves. Compared with the UCODEA charcoal stove, the Lakech stove is smaller both in height and in volume of the charcoal holder. The Lakech stove is widely used in Ethiopia.

Wood lump charcoal, rather than compressed briquettes, was used in the tests because lump charcoal is typically used in the field. Fuels were analysed for energy content using ASTM Standard Method (ASTMD 4442-92) (Bailey *et al*., 2004), and fuels were analysed for heat of combustion using ASTM Standard Method (ASTM D5865-04) (Liu *et al.,* 2008). Reported results for the UCODEA stove indicated a higher thermal efficiency at *high* power setting compared to the Lakech stove, and a similar efficiency between the stoves at low power. The UCODEA stove produced lower emissions compared to the Lakech stove. Additional height of the stove may have provided more room for the circulation of air, thus increasing the combustion efficiency of the stove.

Jetter & Kariher (2009) reported that the Lakech stove has poor thermal efficiency due to its small fuel chamber compared to the UCODEA. Jetter & Kariher contended that the Lakech stove would have performed better if it had been evaluated using a lower fuel load and a small pot size (small amount of water) during the tests. The authors are drawing attention to the difference in trying to standardise a test that does not match the pot to the appliance thereby creating a bias in the standardisation of the test method. Hence, conclusive results could have been obtained if the stoves were evaluated using a variety of fuel loads, fuel sizes, and pot sizes across the stoves full range of power settings.

The Sazawa charcoal stove was designed by Tanzania Traditional Energy Development and Environment Organization (TaTEDO) in the light of poverty reduction and conservation. Since 1990, TaTEDO has been involved in the development of renewable energy technologies (RETs), adaptive research, development and promotion of the technologies to the communities through awareness creation and training (Pesambili *et al*., 2003). The Sazawa charcoal stove is made up of a metallic cladding and two clay liners. Other parts of the Sazawa include a bent round bar that acts as a pot rest, legs, handles, metallic belt, ash collector, and a door for primary air inlet. The firebox has a mean diameter of 250 mm, a height of 220 mm, and primary holes diameter of 15-22 mm (Pesambili *et al*., 2003). A typical Sazawa stove is illustrated in Figure 2.

The Water Boiling Test (with no reference) was adopted for performance evaluation of the Sazawa stove. A thermal efficiency number of 44% was reported for the boiling task (Pesambili *et al*., 2003). However, Pesambili *et al*. (2003) did not explicitly specify pot sizes and the volume of water used in the experiments nor did they indicate how the firepower of the stove was increased or lowered. Again, the experimental procedure was not clearly spelled out to remove doubt as to what the tester ought to do. They did not show in their report an appreciation of factors that affect the performance of a fuel/stove combination.

Figure 2: A typical Tanzanian Sazawa charcoal stove (Photo credit: Pesambili *et al*. 1993)

The prototype SEES charcoal burning stove designed for purposes of cooking, hot water and space heating has been described by Kshirsagar (2009). The stove is built of thin mild steel sheet for low heat absorption by the stove body. A skirt (a metal sheet envelop surrounding the pot) is sued to guide flue gases through the gap/cavity and is important to avoid loss of generated heat energy. The stove also comprises of a metallic water jacket which can be filled with water. The steam from the water jacket is directed to the hot burning charcoal bed. The air trapped between jackets will act as an insulator reducing the outer surface temperature (Kshirsagar, 2009). Low thermal conductivity insulation (glass wool and rock wool) is applied around the stove to conserve generated heat without smoke (Kshirsagar, 2009).

The test procedure followed during the experiments was a simplified version of UCB/Shell Foundation revision of the 1985 VITA International Standard Water Boiling Test, almost identical to that of wood burning stoves (Kshirsagar, 2009). The volume of water used in each experiment was reported to be 1.3 litres. The tests reported a lower thermal efficiency of 21% because the heat produced was absorbed by the water jacket before it reached the bottom of the pot (Kshirsagar, 2009). Temperature of water in the pot was reported to fluctuate between 82 - 88ºC and this was attributed to the absence of insulation and the presence of water in the jacket. Without use of the water jacket, thermal efficiency was reported to increase by 6% and was reported to increase by a further 15% if insulation is used. Tests reported that pot immersion improves thermal efficiency but a large skirt gap reduced efficiency by 12%. Large skirt gap could increase air flow area around the pot decreasing flue gas velocity, which decreases *Reynolds number*. This in turn reduces the value of heat transfer coefficient and hence heat transfer efficiency (Kshirsagar, 2009).

Efficiencies and emission factor values for various Indian charcoal burning stoves were reported by Bhattacharya *et al*. (2002). Thermal efficiencies of these charcoal-fired cookstoves varied widely in the range 12-27%. These were comparable to those found by Kaoma (1994). Bhattacharya *et al*. (2002) reported emission factors for pollutants CO, CH_4, TNMOC in the ranges 35–198, 6.7–7.8 and 6.5–9.7 g kg^{-1} of fuel, respectively.

Illustrative examples presented in this chapter indicate that, while adopted as a baseline, the WBT is being used with multiple variations, with results that are no longer directly comparable. This presents a challenge to develop protocols that are robust, flexible, and adaptable to different fuel/stove types, while resulting in comparable results without further calculations. The following sections discuss development of protocols and standard operating procedures for evaluation of stove performance.

2.9 Protocols and Standard Operating Procedures

Due to the need for certification of stoves and carbon credits under the Kyoto protocol Clean Development Mechanisms, there is now a strong drive aimed at creating protocols and standard operating procedures in performance evaluation of stoves that simulate real-world use of the devices. A protocol is an agreed standardised way of performing a standard task and it is a process that is repeatable and reproducible. There is a consensus that protocols should be divided into general areas and specific procedures detailed separately (http://tech.eanm.org/tech_write_protocols.pdf). In a research laboratory protocols are needed for safety, to operate analytical equipment correctly, and to analyse and report data with minimal mistakes (FEMA, 1999).

The basic types of elements that must be part of a complete protocol specification include:

- The *service* to be provided by the protocol.
- The *constraints* of the environment in which the protocol is executed.
- The *vocabulary* of messages that is used to implement the protocol.
- The *encoding* (format) of each message in the vocabulary.
- The *procedure rules* governing message exchanges (Holzmann, 1992).

At the core of the protocol design is compilation of a consistent set of procedural rules. After the development of protocols some feel there is a need for the development of standard operating procedures (SOPs) that are specific to a given task (EPA, 2007). The SOPs are inherent in protocols, which often cover a range of activities.

2.9.1 *Standard operating procedures (SOPs)*

A standard operating procedure (SOP) is a set of written instructions that document a routine or regularly recurring operation/activity that form part of protocols or investigations (EPA, 2007; FAO, 1998). The purpose of a SOP is to enable a competent person be able carry out set operation correctly and always in the same manner to obtain reproducible and defensible results Thus, a written copy of standard operating procedure should always be available at the place where the work is done.

SOPs should be task-based and specific to that task only. The use of different tasks in a single standard operating procedure is often misleading. SOPs are intended to be specific to the organisation or facility whose activities are described; to assist that organisation to maintain their quality control and quality assurance processes; and to ensure compliance with governmental regulations (EPA, 2007). The knowledge and skills that personnel need to perform specific job tasks, manage programs, and validate data are addressed in technical protocols and professional training. Therefore SOPs are not intended to duplicate basic technical information or provide step-by-step instructions for doing routine scientific tasks. Instead, standard operating procedures describe related considerations: instrument specific procedures, safety related issues, equipment and reagents, source and use of supplies, equipment maintenance, duties and rights of personnel, command structures, coordination with other organisations, and data reporting requirements (FEMA, 1999:3).

2.9.2 *Writing styles for standard operating procedures (SOPs)*

Standard Operating Procedures should be written in a concise, step-by-step, easy-to-read format (EPA, 2007; Stup, 2001; FEMA, 1999). Steps in SOPs are written as imperative sentences, which are in the form of a command and are easy to understand. They usually begin with an action verb (Wieringa *et al.,* 1998). The information should be explained clearly and explicitly to remove any doubt as to what is required. Flow charts may be incorporated to illustrate the process being described.

If not written correctly and concisely, the SOPs are of limited value.[12] Well-written standard operating procedures (SOPs) provide direction, improve communication, reduce training time, and improve work consistency (Stup, 2001).

[12] Mike Solandini in his book entitled *Employee Training and Development with Standard Operating Procedures* (Second Edition). See www.bin95.com/ebooks/write-SOP-example-2.pdf

2.9.3 *Preparation of SOPs*

The organisation should have a procedure in place for determining what procedures or processes need to be documented. The standard operating procedure development process is critical to successful implementation of SOPs (Stup, 2001). These SOPs should be written by individuals knowledgeable with the activity and the organisation's internal structure (FEMA, 1999). The SOP developers are essentially subject-matter experts who actually perform or supervise the work. Thus, there is need to present the SOPs in sufficient detail so that someone with limited experience with or knowledge of the procedure, but with an appropriate basic training, can successfully reproduce the procedure when unsupervised (EPA, 2007; Stup, 2001).

2.9.4 *Review and approval of SOPs*

There is need for standard operating procedures to be reviewed (validated) by one or more individuals with appropriate training and experience with the process (EPA, 2007). It is especially helpful if draft SOPs are tested by individuals other than the original writer before the standard operating procedures are finalised. Any steps that cause confusion or hesitation for the test worker should be revised (Stup, 2001).

The finalised SOPs should be approved as described in the organisation's quality management plan (QMP) or its own standard operating procedure for preparation of diverse SOPs. The finalised SOP will then need to be signed; signature approval indicates that an SOP has been both reviewed and approved by management (EPA, 2007; Stup, 2001; FEMA, 1999). Whenever procedures are changed, SOPs should be updated and re-approved. If desired, pertinent sections of the SOPs are modified and the change date/revision number for the section highlighted in the SOP (EPA, 2007).

Standard operating procedures need to be systematically reviewed on a periodic basis to ensure that the policies and procedures remain current and appropriate (EPA, 2007; Stup, 2001). The review date should be added to each SOP that has been reviewed and if it describes a process that is no longer followed, it should be withdrawn from the current file and archived (Stup, 2001). Comments received during this review often contain valuable insights on the feasibility of the SOP, helping to identify problems before they occur (FEMA, 1999). The review process should not be overly cumbersome to encourage timely review. Management can indicate the frequency of review based on the organisation's quality management plan (QMP). The quality management plan needs to indicate the individual(s) responsible for ensuring that SOPs are current (EPA, 2007).

2.9.5 *General format of a standard operating procedure*

There is no one 'correct' format when it comes to standard operating procedures. Internal formatting will vary with each organisation and with the type of SOP being written (EPA, 2007; Stup, 2001; FEMA, 1999). The level of detail provided in the SOP may differ depending on whether the process is critical, the frequency of that procedure being followed, the number of people who will use the SOP, and where training is not routinely available (EPA, 2007). SOPs should be organised into a logical framework, using headings and sub-headings that help clarify functional relationships and the roles played by different groups. Most experts recommend that departments divide the standard operating procedure manual into separate sections for administration and operations purposes (FEMA, 1999).

In general, technical (analytical) standard operating procedures consist of five major sections: title page, table of contents, procedures, quality assurance/quality control, and references (EPA, 2007; Stup, 2001).

Title page

The first page or cover page of each SOP has to be informative in order to catch the attention of the reader. It should contain the following information: a title that clearly identifies the activity or procedure; a SOP identification (ID) number; date of issue and revision; the name of the applicable agency, division, and branch to which this SOP applies; and the signatures and signature dates of those individuals who prepared and approved the SOP (EPA, 2007; Stup, 2001). The title is essentially for ease of reference and usability (FEMA, 1999).

Table of contents

A table of contents may be needed for quick reference, especially if the SOP is long, for locating information and to denote changes or revisions made only to certain sections of an SOP (EPA, 2007).

Procedures

The following are sections that may be appropriate for inclusion in technical SOPs. Not all will apply to every procedure or work process being detailed. These sections have been adopted from the standard operating procedure format developed by the Desert Research Institute (DRI), Nevada.

- Scope and applicability: describing the purpose of the process or procedure; organisation or regulatory requirements; and limits to the use of the procedure.
- Measurement principle: a set of observations that reduce uncertainty where the result is expressed as a quantity.
- Measurement interferences and their minimisation: describing any component of the process that may interfere with the accuracy of the final product.
- Ranges and typical values of measurement: the limit of measurement values that an instrument is capable of reading. The dimension being measured must fit inside this range.

- Typical lower quantifiable limits, precision and accuracy: describing the precision of an analytical procedure, which expresses the closeness of agreement (degree of scatter) between a series of measurements obtained from multiple sampling of the same homogeneous sample under prescribed conditions.
- Personal responsibilities: denoting the minimal experience the user should have to complete the task satisfactorily, and citing any applicable requirements, for example certification.
- Definitions: identifying any acronyms, abbreviations, or specialised terms used.
- Related procedures: SOPs which should be read in conjunction with this document.
- Equipment and supplies: listing and specifying, where necessary, equipment and instrument characterisation, maintenance, materials, reagents, chemical standards, spare parts, and paper work.
- Procedure: identifying all pertinent steps, in chronological order, and the materials needed to accomplish the procedure such as: instrumentation; method of calibration and standardisation; sample collection; sample handling and preservation; sample preparation and analysis; troubleshooting; data acquisition; calculations and data reduction requirements (such as listing any mathematical steps to be followed); and computer hardware and software (used to store field sampling records, manipulate analytical results, and report data).
- Data and records management: identifying any calculations to be performed, forms to be used, reports to be written, and data and record storage information.
- Quality control (QC) and quality assurance (QA): quality control activities are designed to allow self-verification of the quality and consistency of the work. Each measurement consists of a value, precision, accuracy, and validity. Quality assurance integrates quality control, quality auditing, measurement method validation, and sample validation into the measurement process. Quality control is intended to prevent, identify, correct, and define the consequence of difficulties, which might affect the precision and accuracy, and validity of the measurements. The limits/criteria for quality control data/results and actions required when quality control data exceed quality control limits or appear in the warning zone should be described (EPA, 2007).
- Reference: documents or procedures that interface with the SOP should be fully referenced (including version numbers) such as related SOPs, published literature, or methods manuals.

The formats of the SOP help in presenting well defined sets of procedures to people not expert in the task. SOPs must be effectively implemented within the department to have the desired impacts, which include improved safety and enhanced performance on the job (FEMA, 1999). Since the standard operating procedures control the quality of the work performed by people who are not expert in a task, they are clearly critical to the proper running of an institution or analytical laboratory.

CHAPTER THREE

In this chapter innovative developments in stove testing protocols are motivated and apparatus used to carry out these protocols are described in detail. A range of seven paraffin and solid fuel stoves that were evaluated for thermal and emissions performance are described in terms of their characteristics. The elements of the test procedure making up a full test protocol are identified and discussed including emission factors, thermal performance and fuel consumption. Aspects of quality control and documentation of protocols and standards are presented herein.

3. Materials and Methods

This chapter describes the experimental tools used in the development of testing protocols and standard operating procedures for performance evaluation of diverse fuel/stove combinations. Section 3.1 describes in detail stoves that were evaluated for thermal efficiency and emissions performance. A detailed description of the mechanism and dimension of each stove is given. Selected parameters to be incorporated in a new protocol and standard operating procedures are presented in Section 3.2. Section 3.3 details the experimental procedure for assessment of thermal and emissions performance of the listed stoves. Quality control measures are presented in section 3.4 and the presentation of protocols and standard operating procedures for documentation purposes is highlighted in Section 3.5. Care is given in explaining how the standard operating procedures are defined in the protocols. The last section of this chapter presents a conceptual comparison between the new stove testing protocol and the widely used Water Boiling Test (WBT) version 3.0. The section addresses the necessity for such a comparison in the light of requirements for improved health, CDM and Gold Standard (premium quality carbon credits) projects for carbon reductions or offsets, and more detailed assessments of fuel/stove combinations.

3.1 Description of Stoves

The objective of this section is to present in detail a technical evaluation of the stoves used in the experiments and to present an understanding of how the differences in stove design and operating mechanisms potentially affect stove performance. Special interest is given to various models of paraffin stoves in order to illustrate strengths and weaknesses of the developed protocols in meeting the requirements, in particular, for CDM and Gold Standard carbon reduction projects. Descriptions of the various dimensions and technical aspects of paraffin stoves were adopted from an MSc thesis on design of paraffin stoves (Bradnum, 2007), and from a series of conversations with the same author.

3.1.1 The baseline paraffin wick stove

The stove is of barrel-shaped sheet metal construction with a series of vertical slots on its sides. It has a set of two wide crescent wicks. The stove has a powder-coated surface and is normally available in two colours (maroon and blue). This stove has a potholder with three pot stand-offs mounted on top (Figure 3).

Figure 3: Baseline paraffin wick stove
(Photo credit: T. Makonese)

The stove has a wick configuration which consists of two woven fibre-glass mats which are formed into crescent shapes and fitted into bent aluminium retainers. "*The wick mechanism works with a single closed top inner diffuser and a double outer diffuser"* (Bradnum, 2007:26). The retainers have tabs that allow them to be fitted to a base plate. This whole unit is then slotted into the wick housing. The controller is held within the wick housing and has a round gear with teeth at its end. The gear works in conjunction with a vertical gear that is attached to the moving wick sleeve/base plate mechanism. The moving gear on the wick mechanism is held in place by a wire which prevents it disassembling from the wick housing. "*On the wick housing a set of bent sleeves allow the wick mechanism to slide up and down as the controller is adjusted. Spot-welding holds these components (top and base)"* (Bradnum, 2007:26) the correct distance apart on the wick housing.

3.1.2 The new type paraffin wick stove

This stove evolved out of the model described above, taking into account additional safety requirements identified by the SABS paraffin stove safety standard (SANS 1906: 2009). As above, the stove has a double shaped wick configuration. Each of the two wicks is made from woven fibre glass. The stove has a tripod leg construction riveted at the base of the fuel tank (Figure 4). The tripod structure holds the pot rest away from the fuel tank.

The mesh around the diffuser allows for circulation of air for combustion. The diffuser configuration on this stove includes a closed top (with a small hole in the centre where a metal cup with circular holes protrudes), inner diffuser and a double walled outer diffuser. The gap created between the inner and the outer diffuser allows air to come into contact with the wick (Bradnum, 2010; personal communication).

The controller is held in place within the wick housing. It has at its end a round gear with teeth. This gear works in conjunction with the vertical gear that is attached to the moving wick and the top metal cap. When the wick moves up, the metal cap moves up leaving a gap for the diffusion of air into the combustion area of the stove. The upward movement of the wick and the metal cap result in an increase in the size of the flame and the fire-power of the stove. Both diffusers heat up quickly during stove use. This allows air to be pre-heated before reaching the flame zone, thereby increasing the combustion efficiency of the stove (Bradnum, 2007).

The controller is connected to an external lever (Figure 4). The lever relies on a friction traction mechanism to function properly. If the stove is tilted or moved slightly, the lever triggers causing the wick to retract and the top metal cap to close the top of the stove, shutting it down instantly. The increased distance between the combustion zone and the fuel tank ensures that the temperature of the fuel does not reach the flash point, even after prolonged usage of the device, a critical design flaw in the baseline paraffin wick stove.

Figure 4: The new type paraffin wick stove
(Photo credit: T. Makonese)

3.1.3 The pressurised paraffin stove

The stove uses a *roarer* type burner.[13] The fuel tank has a filling inlet which includes a pressure release screw valve and a sealed fuel cap. The tank has a pressure pump protruding from the side of the tank (Figure 5). The pump's internal end is a one way air valve allowing air to be pumped into the fuel vessel.

According to the manufacturer's instructions, the stove should be ignited using methylated spirits to fill the pre-light cup. However, most users use paraffin as a pre-light fuel instead of methylated spirit. This is done by pressuring the stoves pump, allowing paraffin to flow out the nozzle to fill the pre-light cup, then releasing pressure when the pre-light is nearly full. An asbestos swab is used to light the fuel in the pre-light cup. Once the area has been engulfed in a flame for one minute, the pressure valve is sealed and the stove is pressurised until the required flame is obtained. Pre-lighting the stove heats both the inner and outer tube and the burner head. This configuration becomes hot, thereby vaporising the paraffin as it passes into this area. The nozzle then sends a stream of this vaporised paraffin vertically to the chamfered underside of the copper head (Bradnum, 2007). This vapour mixes with air causing, allowing combustion to take place around the copper head.

The stove is controlled by a combination of pressure and release. The higher the pressure within the fuel vessel the stronger the flame and the more heat is generated. The user is required to release pressure to lower the fire-power of the stove. In order to extinguish the flame, the user releases all the pressure from the fuel vessel, thereby cutting fuel supply to the head (Bradnum, 2010; personal communication).

Figure 5: Pressurised paraffin type (non-wick) stove (Photo credit: T. Makonese)

[13] A *roarer* type burn is one which produces a distinct jet-like sound when in use.

3.1.4 *The imbaula coal stove*

Imbaula (brazier type) stoves are hand-made out of round metal drums with perforations of varying sizes around the sides, and a wire grate across the middle of the container to hold the solid fuel. *Imbaulas* are found in three characteristic sizes, determined by three commonly available metal drums: 20 litre metal paint drums, 70 litre metal dustbins, or sectioned 200 litre oil drums. A typical 20 litre *imbaula* is illustrated in Figure 6. *Imbaulas* commonly have a fuel support grid, made of wire or a perforated plate, but some are operated without a fire grate. With this fire grate in place the rate of burning is increased.

It should be noted that there is no standard *imbaula,* as the devices vary greatly in terms of the number and sizes of the side holes, the presence of a grate and its position in the metal drum. These metal drum stoves are used widely in the townships of South Africa for space heating and cooking, especially in winter. The stoves can burn wood, coal, or a combination of both, and often rubbish which include can include waste plastic. The stoves are widely used in winter for space heating and cooking.

Figure 6: A typical South African Highveld *imbaula* (Photo credit: D. K. Kimemia)

3.1.5 *The traditional Mozambican metal charcoal stove*

The traditional Mozambican metal stove is a portable, metallic, single pot stove without a chimney (Figure 7). It is designed for use with charcoal, but can burn wood or a variety of agricultural residues. The stove is equipped with a fixed grate with the lower chamber acting as an ash collecting zone. The lower chamber can also be used as a combustion chamber when burning woody biomass fuels and agricultural residues. The stove is rectangular in shape with a metallic base and four legs. The stove illustrated is 390 mm high, 225 mm wide and has a depth of 220 mm. The stove has a mass of 3.3 kg. The grate is made up of 15 bars with an average diameter of 8 mm.

Figure 7: Traditional metal Mozambican charcoal stove
(Photo credit: T. Makonese)

3.1.6 The new type ceramic Mozambican charcoal stove

The recently introduced Mozambique *Poca*® stove is made up of a ceramic body with an outside top diameter of 235 mm, a bottom diameter of 280 mm and a height of 200 mm (Figure 8). The stove weighs approximately 4.5 kg. The special design features include a conical rim with slanted pot rests. The inward curving ceramic grate has a depth of 65 mm with 13 equally distributed holes. The average diameter of the perforations is 13 mm. The grate diameter is 210 mm. The stove uses charcoal as fuel.

Figure 8: The new type ceramic Mozambican charcoal stove
(Photo credit: T. Makonese)

3.1.7 The bottom-lit down-draft coal stove

Bottom-lit down-draft (BLDD) devices are promising candidates for meeting at least the basic demand of low emissions. This innovative prototype stove is made of cast iron and uses coal as fuel (Figure 9). The stove is still under development at the SeTAR Centre, University of Johannesburg (Pemberton-Pigott *et al*., 2009). Kindling is placed on the grate, with coal loaded above in a hopper. Air is passed through the fire zone from the top of the hopper downwards. The BLDD is able to maintain a downward projecting flame below the level of the grate because the ash continually falls away exposing burning coke. In principle, the BLDD uses gravity and the draft to dispose of ash.[14]

Figure 9: The prototype SeTAR bottom-lit down-draft coal stove
Note: shown here is the BLDD stove loaded with wood for ignition
(Photo credit: T. Makonese)

3.2 Selected Parameters to be Incorporated into a New Protocol

The standard *Water Boiling Test* (WBT) Version 3.0 (Bailis *et al*., 2007b) has been used extensively for the evaluation of stove performance (MacCarty *et al*., 2010; Johnson *et al*., 2008; Berrueta *et al*., 2008; Johnson *et al*., 2007; Boy *et al*., 2000), and the stove development community (ETHOS) have engaged in several rounds to develop the test and the data processing procedures. Specifically the work of Taylor (2009) has examined in depth the WBT. Taylor

[14] Most of the development work on BLDD stoves has been carried out at the University of Johannesburg by Crispin Pemberton-Pigott with some larger versions produced in Mongolia (Pemberton-Pigott & Lodoysamba, 2011).

cautions: "…*in developing modifications of the existing protocol, several criteria should be kept in mind:*

1. *Fuelling: Fuel should not be added to a batch-fed stove while it is in operation.*
2. *Operation: No portion of the test should require operating the stove outside its design parameters.*
3. *Safety: Test modifications should not negatively impact the safety of the operator.*
4. *Intent: Modifications to the test should not violate the spirit and intent of the original test.*
5. *Broad acceptability: Where possible, modifications should also be applicable to continuous-feed or mixed-feed stoves; that is, ideally the modifications should not 'break' the test for these other stoves*." (Taylor, 2009:36).

On the basis of a needs assessment of stoves within the southern African region, we identified that a test procedure would require additional variants of selected parameters for evaluation of thermal and emissions performance of the stoves. Parameters considered were: pot sizes (3 litres and 6 litres, with pot lids); power settings of the stove (*high*, *medium*, *low*); and fuel type and load (manufacturer's instructions versus common household use). These parameters were selected because they are often ignored in many evaluations of solid fuel/stove combinations, yet they reflect real world uses of the fuel/stove combinations. Furthermore, these parameters are often not highlighted in existing stove testing protocols. It is important to note that during the tests we did not use oven dried fuel of prescribed shape and size as per WBT Version 3.0. By allowing a range of *as received* fuels, our proposed set-off criteria fell outside the intent of the WBT Version 3.0, which eliminated the variability of moisture content and fuel type by requiring use of a constant fuel – wood – in an oven dried state. As water content significantly alters thermal and emission performance of many stoves, control of this variable is clearly a good strategy for reducing the complexity of testing protocols. This standardisation leads to test results that do not reflect real-world uses of fuels and stoves. By relaxing this variable, our proposed protocol fell outside the cautions articulated by Taylor, and hence the new protocol developed and described here should be regarded as an entirely new and different test, not as a derivative or refinement of the WBT. Other major differences evolve in the calculation of the emissions, which will be developed in later sections.

Even though criteria proposed by Taylor (2009) were used in the development of a new stove testing protocol, the alternative tests proposed are not similar in principle to the WBT save for the standardised task of boiling water. The following sections outline some of the important parameters not highlighted in the WBT which were incorporated into the new protocol.

3.2.1 Pot sizes

The combustion efficiency, thermal efficiency and emissions performance of a fuel/stove combination vary based on the fuel and on the coupling between the stove and the pot. Hence the applicable stove test should strive to run the test with a range of pot shapes and sizes spanning typical use. For example, in most parts of southern Africa, cooking involves the use of different pot sizes with pot lids on (the smaller pot is used for the preparation of relish and the larger pot for the staple – generally a thick maize porridge). Dominant test protocols in wide use today such as the WBT Version 3.0, requires using a single standardised test pot (Bailis *et al.,* 2007b). This was intended to make tests of different stoves directly comparable, but has led to accusations that the test is designed around a specific stove, and that the protocol encourages designs optimised for a single pot size that may be atypical to the intended market for the stove (Taylor, 2009).

In this study two different pot sizes (3 L and 6 L) with different water volumes (2 L and 5 L) will be used in the tests. The stoves will be evaluated for thermal and emissions performance using these two pot sizes with the lids on. The VEG Gas Institute in the Netherlands uses a simple formula to select pots for testing. Their recommended heat flux through the pot bottom at an efficiency of 50% is 7 W cm^{-2} (Rani *et al*., 1992; Bussmann, 1988).[15] Bussmann (1988) recommends higher power densities for wood stoves as the thermal efficiency is lower. He reported power densities of 7 W cm^{-2}, 10 W cm^{-2}, and 17.5 W cm^{-2} bottom areas at efficiencies of 50%, 35% and 20% respectively.

Different opinions arise concerning the use of pot lids. It is argued that pot lids improve performance of the stove yet the main purpose of the WBT Version 3.0 is to quantify the way that heat is transferred from the stove to the cooking pot (Bailis *et al.,* 2007b). VITA (1985) suggested that if the testing area is properly shielded from draughts, lids may be avoided, otherwise they may result in an increased rate of evaporation, thus making the relevance of the figures of merit obtained quite debatable (Rani *et al*., 1992). Our approach is based on the premise that the fuel, stove, pot (including the lid), and the operator represent a complete cooking system and the use of pot lids shows good cooking practice. Since in most cases pot lids are used for the actual cooking task, it is imperative to use them when conducting tests. Open pots can complicate the test by increasing the variability of the emissions performance outcome and making it harder to compare from different tests: "…*by not using a lid, evaporation rates are higher and the stove must be run at a somewhat higher power to maintain the temperature than is the case with a lid.*" (Baldwin, 1987:255).

[15] The units used are presented as reported by the cited authors, rather than converting to SI units.

3.2.2 *Power settings*

In this study fuel/stove combinations will be evaluated for thermal and emissions performance across a full range of power settings. A stove is usually operated over a full range of power settings for the preparation of meals. A common occurrence is the use of a *low* power setting for simmering and space heating, especially in winter. Furthermore, what is normally referred to as the *low* power setting can often be a power setting not very different from *medium* power. Baldwin (1987) contends that it is difficult to simmer at the *low* power setting if the tests are carried out without a lid, thus the need for a 'somewhat' higher power setting to achieve simmering. The WBT version 3.0 does not suggest testing stoves across a range of power settings, thus the *turn down ratio* parameter as calculated in the WBT spreadsheet may be a deceptive or somewhat arbitrary performance indicator.

3.2.3 *Fuel type, fuel size and fuel loads*

Widely used stove testing protocols for solid fuel stoves (wood, charcoal and coal) are prescriptive in the type, size and moisture content of fuel used, in an effort to derive a standardised test. The reason for using a specific fuel size and moisture content is to try to avoid complexities in emissions due to water shift reaction and variable thermal performance exhibited by different moisture content fuels. Attempting to control this important variable from solid fuel *as received* imposes artificial conditions on the test method and analytical measurements. If this variable is not controlled, the protocol becomes more sophisticated and would require the determination of total O_2 and H_2 in the gas stream, and a determination of the moisture content of each batch of fuel at the time of testing. An important analytical technique will be to allow the fuel moisture content to vary but to fully account for it in all stove performance spreadsheet calculations of the test. This is done because the introduction of standardised fuels imposes conditions that are often unrepresentative of real-world uses or likely combinations of fuels, stoves, and pots. The WBT Version 3.0 protocols require using a standardised fuel: "…*try to use only wood (or other fuel) that has been thoroughly air-dried. Wooden stocks 3-4 cm in diameter…testers should try to use only similar sizes of wood to minimise this source of variation…drying the sample completely in a controlled manner…*" (Bailis *et al*., 2007b:5, 10). This has led to accusations that the protocol encourages designs optimised for a single fuel that may be atypical of the intended use of the stove (Taylor, 2009).

To better reflect the real world use of these devices, the new protocol will be adapted in two key areas. Firstly, as performance can be affected by the quantity of fuel that is batch loaded into the stove, the protocol will require that tests are conducted with two discrete fuel masses which either reflect common use or manufacturers' recommendations. Secondly, rather than control the power output of solid fuel burning stoves by continually adding fuel at different time intervals to maintain a desired firepower, a single charge of fuel will be used and the fuel left to burn through a full cycle (from ignition to smouldering).[16] Thermal efficiency and emissions performance will then be assessed over two or three phases of the fire (e.g. ignition, pyrolysis, smouldering) or based on a task (e.g. heating water, boiling, simmering). Most importantly, the protocol will allow for the use of a variety of fuel types, fuel sizes, fuel moisture and fuel loads for which the stoves were designed including wood pellet burning stoves which proved to be almost impossible to test using the WBT 3.0. The variability in fuel composition and size will be accounted for in the spreadsheet calculations for evaluation of thermal and emissions performance of each fuel/stove combination.

3.2.4 Hot start and safety

The hot start phase of the WBT is a *high* power test. It follows immediately after the first test (cold start) while the stove is still hot. A pre-weighed bundle of fuel is used to bring to the boil a measured quantity of water in a standard pot. The intent of this part of the test is to identify differences in performance between a stove when it is cold and when it is hot (Bailis *et al*., 2007b).

The WBT Version 3.0 suggests the fuel left at the end of the hot-start section be put back into the stove and re-lit, and further assumes that fuel can be added to the stove as necessary (Taylor, 2009). The simmering phase of the WBT version 3.0 is difficult to apply to batch-fed stoves. Taylor (2009) suggests that rather than placing hot fuel into the stove at the beginning of the simmer phase of the WBT, the tester should allow the stove to cool down until it is safe to re-fuel it with a new charge of unburned fuel. This is in contrast with the current procedure which calls for replacing a hot mix of unburned and partially-burned fuel into the stove and relighting it. However, this modification defies the essence of hot starting in the first place; that of using a hot stove for the second phase of testing.

The art of building a new fire in a stove that is still hot from the previous fire (hot-starting) is difficult and unsafe in some batch-feed stoves because fuel cannot be easily loaded when the stove is hot. The hot-start portion of the test should only be performed if it proves meaningful to real-world uses of stoves. "*The logic of omitting a test procedure in cases in which it is unsafe or meaningless in terms of real-world use should stand on its own without further explanation*." (Taylor, 2009:39). Hot starting was not included in the new protocol for thermal and emissions performance because the stoves evaluated had lower thermal masses (they quickly cooled down when hot fuel was removed from the stove for sorting), and again it proved dangerous to do so with liquid fuel stoves.

[16] This method referred to as the *burn-out method* was originally suggested and recommended for use by Crispin Pemberton-Pigott as an alternative to using the Indian method (Funk, 2000) which requires repeatedly putting on fresh pots of cold water.

3.3 Experimental Procedures, incorporated in the Heterogeneous Testing Protocol

The experimental procedures to be described in this chapter cover the tests for thermal efficiency, emissions performance, specific fuel consumption, fire-power, fuel burn rate and turn down ratio. Overview procedures are presented in the text of the chapter. Standard operating procedures, with detailed task and instrument descriptions (which were one of the outputs of this project) are presented in the appendices. This overall collection of tests and methods described in this chapter and presented in the form of *Standard Operating Procedures (SOPs)* in the appendices, is what we have termed the *Heterogeneous stove Testing Protocol (HTP).* The practical methods of the tests are presented in this chapter. As the full protocol is one of the outputs of this thesis, the motivation and development of the structure, and examples of the SOPs are presented in the Chapter 4: Result, together with representative results of the protocol applied to the testing of a range of stove types.

Specifically, the procedures are described for three sets of tests that were carried out as part of the practical tasks of this research programme:

- A comparative evaluation of *gas emissions* from three paraffin stoves
- Characterisation of *combustion efficiencies* from Top-Lit Up-Draft (TLUD), Bottom-Lit Up-Draft (BLUD) and Bottom-Lit Down-Draft (BLDD) coal burning stoves.
- Measurement and comparison of the *thermal performance* of a suite of stoves comprising a baseline paraffin, an improved paraffin, a baseline metal charcoal, and an improved ceramic charcoal stove.

3.3.1 Choice of cooking pots

The pots used in this study are Hart™ aluminium 3 L and 6 L capacity pots, commercially available and widely used for cooking in South Africa and regionally. For the water heating tasks, an amount of water (either 2 L or 5 L for the small and large pots respectively) was heated from ambient temperature to the target temperature (boiling or 70°C) at the respective power settings. For certain stoves designed for small pots only, tests with the larger pot were excluded, e.g. the camping gel stove, intended only to boil water for two cups of tea.

A pot was used together with the lid it was designed for, and the lid was equipped with a 10 mm diameter pipe protruding not more than 5 mm below the lower surface of the lid, which discharges steam outside the extraction hood. In this way, steam from the pot is removed from the gas stream being analysed. The pipe must always run upwards from the pot to prevent any pools of condensate from forming in the pipe. Again, it is important to remove the steam from the combustion flow because it would complicate the analysis of the combustion gases. Excess water vapour has the potential to render the drier on the flue gas analyser less effective than it should be.

3.3.2 Emissions performance test

The *hood* method was used for evaluating emissions from paraffin, charcoal and coal burning stoves. The stove to be tested is placed under an extraction hood (Figure 10). The probe of the analyser was inserted in the chimney for stoves with flue (for example, the BLDD coal stove). For stoves without a flue, the stoves were placed under a collection hood and the probe was placed inside a hood exhaust duct. Since a high extraction rate may influence the combustion characteristics of the stove (Bhattacharya *et al.,* 2002), an extractor fan was not used for drawing air through the hood and duct. The sampling configuration for gases included, in sequence, a stainless steel probe, a filter holder, and a flue gas analyser (Testo® 350XL/454). The Testo® measures CO_2, CO, NO, NO_2, H_2, H_2S, SO_2 and O_2**.** For a detailed operating procedure for using the Testo® XL350/454 for emission measurements, refer to Appendix B.

The *hood* method can be used simultaneously with that for the determination of thermal parameters (procedure for thermal parameters is described in Section 3.3.3). This has the added advantage of enabling simultaneous measurements of emissions and thermal parameters in a systematic and standard manner (Zhang *et al.,* 1999:355). Figure 10 shows the experimental set-up for the analysis of combustion gases from fuel/stove combinations.

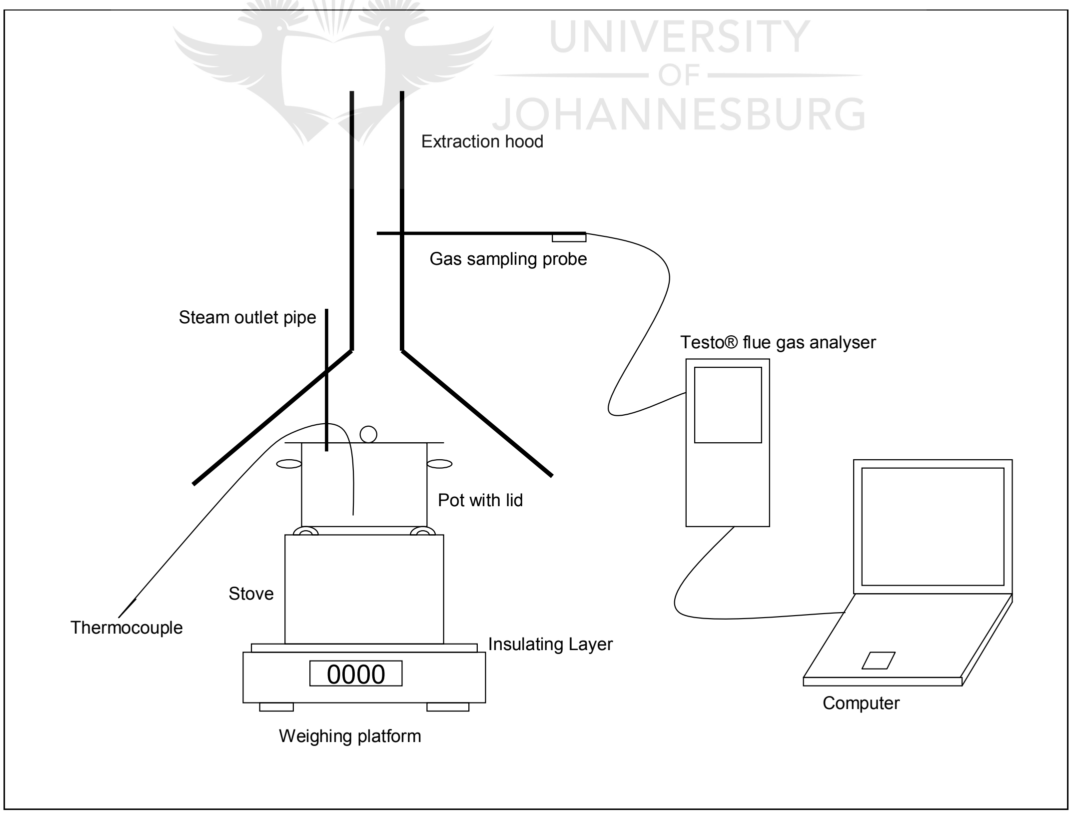


Figure 10: Experimental set up for analysis of combustion gases from fuel/stove combinations (not drawn to scale)

(Drawing credit: T. Makonese)

3.3.3 Thermal performance tests at high, medium and low settings

The thermal performance evaluation comprised three separate tasks at *high*, *medium* and *low* power settings. The *high* power test required heating water from ambient to boiling as rapidly as possible, with each pot size as described in Section 3.3.1. To obtain the specific fuel consumption at the *high* power setting, this test was continued for a minimum of 10 minutes after reaching boiling point. The stove was adjusted to *medium* power and allowed to equilibrate for five minutes, after which a fresh pot of cold water was placed on the stove. Readings were recorded while the water temperature was allowed to rise by 40ºC from ambient to ~70°C, marking the end of *medium* power test. The pot was removed and the power setting adjusted to *low* (that is to the low power stop, or, if none, to the lowest level that kept the flame alive but stable). After equilibrating for five minutes, a fresh pot of cold water was placed on the stove and readings recorded until the water temperature had increased to ~70°C, marking the end of *low* power test.

A digital electricity operated scale with a 32 kg range and a 0.001 kg resolution supported the entire stove, fuel and pot. Mass readings were recorded manually every 60 seconds. Since the mass of the stove and the pot is known, lifting up the pot until the scale has become stable makes it possible to calculate the interim fuel and fire-power, and any water mass. For solid fuels, the mass of the fuel and charcoal remaining at the end of the test were measured for efficiency calculations. All fuels were analysed using a bomb calorimeter (CAL^{2k} ECO® calorimeter) for determination of their calorific values prior to each test.

Other collected data included amount of water vapour generated and amount of fuel burned. These are necessary to determine thermal parameters such as burn rate and overall thermal efficiency of each fuel/stove combination. The total emission mass per standard task was determined from the calculation of pollutant concentrations emitted during the heating up phase, boiling phase, *medium* and the *low* power setting of the stove. For a detailed experimental procedure refer to Appendix A.

3.3.4 Fire-power for fuel/stove combinations

The test procedure for determining the power settings used was similar to that advocated by Prasad *et al*. (1983), but with minor changes. It is important to note that burn rate can be regarded as comparable to fire-power (Bhattacharya *et al*., 2002). The stove was filled with fuel and the mass of the stove and fuel were recorded. The mass of a stove was measured by means of a mass balance on which the stove rested. The mass balance recorded the mass loss due to the fuel's consumption as a function of time. The instantaneous power output of the stove is defined as the mass loss rate multiplied by the lower heating value of the fuel, assuming complete combustion (i.e. products of incomplete combustion are minimal):

$$P = \frac{(LHV \times \Delta m)}{\Delta t} \qquad \text{Equation 7}$$

where P is the fire-power of the stove at a specified power setting (measured in watts); Δt is the time interval; Δm is the mass loss in a specified time interval; and LHV is the lower heating value of the fuel.

The stove was set to its maximum possible power setting (according to manufacturer's instruction or as commonly used) and ignited. The stove was allowed to warm up until a constant rate of fuel consumption was observed. Tests were run according to the procedure described in Section 3.3.3. It is important to note that the constant temperature rise method could only be applied to fuel/stove combinations designed to be operated across a range of power settings. Most solid fuel stoves could only be operated at the *single* power setting, without means of adjustment. A single batch load of fuel was charged at the beginning of the test, and allowed to burn until 90% of the fuel has been used. The fire-power of the stove was calculated as an average of fuel consumed over time from ignition to 90% fuel consumption.

3.3.5 Thermal efficiency

Thermal efficiency (η) is the ratio of work done by heating and evaporating water, to the energy generated by burning fuel, and is mathematically represented as:

$$\eta = \frac{C_p M_w (\Delta T) + M_e L}{M_f (LHV_f) - M_c (LHV_c)} \qquad \text{Equation 8}$$

where M_w is the mass of the water in the pot at the start of the test, C_p is the specific heat capacity of water, (ΔT) rise in the water temperature in ºC, M_e is the mass of the evaporated water, L is the latent heat of vaporisation of water, M_f is the mass of the raw fuel burned, M_c is the mass of the remaining charcoal, LHV_f is the lower heating value of the fuel, and LHV_c is the lower heating value of the residual charcoal (if any).

The formula given in Equation 8 does not account for excess ash which is formed in high ash containing fuels such as coal. This could result in an error in the evaluation of thermal performance of fuel/stove combinations. "*For relatively short tests with most woods, this will not be a large source of error, but with dung or agricultural residue, or with long tests in stoves that are very effective at burning up their char, the counting of ash as char could introduce a serious error.*" (Taylor, 2009:53). The ash may be accounted for by calculating the change in char mass (M_c) as:

$$M_{c\,corrected} = M_c - (M_f - M_c) AC_{fuel} \qquad \text{Equation 9}$$

where $M_{c\ corrected}$ is the mass of the charcoal corrected, M_c is the mass of the charcoal, M_f is the mass of raw fuel, and AC_{fuel} is the ash content of the fuel on a wet mass basis.

Efficiency can only be determined by separating the fuel, char, and ash and by measuring the proportions of each, and calculating the energy content of each. It should be noted that although the method shown in Equation 9 is not recommended as a *standard* way of determining thermal efficiency, it has the advantage of addressing ash content in the material removed from a stove at the end of a test, thereby minimising error. There is a deduction for the mass of free ash that should be present in addition to the char. The energy accounting error (due to ash content) can be avoided and is an important result in terms of test metrics since the error will greatly affect most other outputs of the test. As a result, thermal efficiency will be calculated using the following equation:

$$\eta = \frac{C_p M_w \Delta T + M_e L}{M_f (LHV_f) - M_{c_{corrected}} (LHV_c)} \qquad \text{Equation 10.}$$

"A problem which occurs in evaluating the efficiency of fuelwood stoves is caused by the stoves. Since all the fuel is inside the stove, it is usually required that the fuel be removed from the firebox, measured and replaced. Combined with the added problem of separating the unburned wood and the char this presents major practical problems" (Ballard-Tremeer, 1997:22). For many enclosed stoves it is impractical to remove unburned wood. To get a good indication of the energy released from the fuel it is better to batch load the stoves with fuel and operate them in such a way that only char and ash remains at the end of an experiment (or heating phase). This means operating the stove in a way that does not entirely reflect real-world uses of stoves. However, the equivalent mass of fuel burned, on an energy basis (with reference to the unburned wood), can thus be calculated with reasonable accuracy.

3.3.6 Specific fuel consumption

Specific fuel consumption (SFC) is the ratio between the amount of fuel consumed and the water equivalent of the food cooked. This will be calculated from the mass of the fuel and water used to complete a given task. This entails that the *initial* mass of water be used for the calculation. Mathematically SFC is represented as:

$$SFC = \frac{M_f - M_c}{M_w} \qquad \text{Equation 11}$$

where M_f is the mass of fuel used, M_c is the mass of the charcoal, and M_w is the mass of water used at the start of the test. This is at variance with Ballard-Tremeer (1997), who used the amount of water evaporated, and Baldwin (1987) who used the water remaining after boiling.

3.3.7 Measurement of fuel burn rate and water evaporated

"*Fuel burn rate is calculated as an overall figure during the heating up phase and the simmering phase. Having the stove resting on the scale suggests that the burn rate can be measured continuously*." (Ballard-Tremeer, 1997:23)

The difficulty is that both water mass in the pot and fuel mass are decreasing at different rates, neither of which is constant (Ballard-Tremeer, 1997). Since the mass of the stove and pots are known, lifting the pot from the fire for a few a seconds (until the scale has become stable) makes it possible to calculate the interim fuel and water masses and hence to be able to calculate separately the fuel and water loss rates. All tests were conducted with the pots lifted in this manner, at one minute intervals.

For solid fuel burning stoves, "…*the burn rate was determined by burning a known amount of fuel in a test and measuring the time for 90% of the fuel to be consumed. It was done by putting the stove on a weighing scale and the time was noted when 10% of the initial fuel weight was left"* (Bhattacharya *et al*., 2002:390). This strategy, which we adopted, avoids the uncertainty of deciding when the fire has reached smouldering stage or has died out.

3.3.8 Emission factors

In stove analysis, an *emission factor* (EF) is the term given to a gas concentration that has been normalised for dilution by excess air, to some reference value of residual oxygen. It is not valid to compare the gas emissions from two stoves if each sample has been diluted by a different or unknown quantity of air, which is related to the design or operation of that stove. It is essential to *undilute* the gas sample by *post hoc* calculation, so that the stoves that have high excess air do not get rated as 'cleaner'. The amount of excess air flowing through a stove is quantified (by measurement of the residual oxygen) and then factored out of the emissions measurement to yield a portable figure that makes possible meaningful comparison between stoves.

In this thesis, the term *emission factor* is defined as concentration of a gas emitted by the stove, expressed in parts per million volume (*ppmv*), normalised to 0% excess air (oxygen). It is possible to convert this value to other units such as [$g\ MJ^{-1}$] of fuel. This provides the concentrations in *undiluted* air (i.e. sufficient air to provide stoichiometric combustion). It is common practice to normalise stack emission concentrations to some standard dilution factor. For example, EPA Method 5 stack testing method requires adjustment to 15% residual oxygen content. In the case of non-ducted stove emissions, variable amounts of dilution air cause uncontrolled dilution of the stack gases, hence direct measurement of volume flow rates of primary and post dilution is impractical. For simplicity in representing the results of mass balance of all emissions from complete and partial combustion of the fuel, we have chosen *zero per cent excess air* as a reference value for emission factor reporting.

Excess air expresses how many times the amount of air supplied to the stove is larger than the minimum amount which is theoretically necessary to burn the fuel completely. It is an important factor for the design and operation of stoves to optimise for low pollution emissions. The air supplied to the stove and passed through the fire is 100% of the oxygen needed to combust the fuel, plus the extra that was not used. The excess of air during combustion processes is denoted λ. Most systems calculate the λ factor using Equation 12 on the basis of the known $CO_{2\,max}$ value for the given fuel and the measured concentration of CO_2 in the combustion gases:

$$\lambda = \frac{CO_{2\max}}{CO_{2meas}} \qquad \text{Equation 12}$$

The above formula can be transformed into the form:

$$\lambda = \frac{20.95\%}{20.95\% - O_{2meas}[\%]} \qquad \text{Equation 13}$$

When using the *oxygen balance approach*, the method requires that the chemistry of the stack gases be taken into consideration in order to determine what the actual level of excess air in the stack is. This gives the actual amount of oxygen in the stack that is not needed relative to the amount that was used by the fire. The total air is the oxygen detected plus the oxygen used. For this calculation, we measure all the oxygen containing gases in the stack (CO_2, CO, SO_2, and NO). This means oxygen in the fuel (which is considerable in the case of wood) is part of the oxygen supply, not just air. The following equation can be used for the determination of λ:

$$\lambda = \frac{O_{2meas} - \sum G_{op}}{\sum O_{2\det} - (O_{2meas} - \sum G_{op})} \qquad \text{Equation 14}$$

where O_{2meas} is the amount of O_2 measured and is usually denoted 20.95%, $\sum G_{op}$ is the sum of the oxidising potential of all the detected gases, and $\sum O_{2\det}$ is the total oxygen detected from all gases. This value can be used to compare between stoves to see how cleanly they burn relative to each other. Factored with the mass burned, it yields directly the mass of the gas emitted.

In other contexts the term *emission factor* is used to describe the specific emissions from a stove or other combustion process over a certain time period or cycle, for example, the ratio of total quantity of carbon monoxide emitted per ton of fuel burned. This parameter is useful in studies of atmospheric dispersion and ambient air quality. This example of an alternate definition of the term *emission factor* is a caution that in every report of publication dealing with emissions factors, the exact meaning and mathematical formulation of the term needs to be stated explicitly, to avoid confusion and error.

3.3.9 Turn-down ratio of fuel/stove combinations

The turn-down ratio is reported as a positive real number that is equal to the fire-power of the stove (as defined above) at *high power* divided by the fire-power of the stove at *low power* (Taylor, 2009). The intent of this metric is to report a property of the stove indicating the amount of control the user has over the available heat range. This metric is represented mathematically as:

$$TDR = \frac{P_{\max}}{P_{\min}} \qquad \text{Equation 15}$$

where P_{max} is the fire-power of the stove at *high* power and P_{min} is the fire-power of the stove at *low* power.

In the WBT protocol and spreadsheet, turn-down ratio is defined as the ratio of the stove's *high* power output to its *low* power. The *low* power setting is define here as the lowest power that can keep water simmering at 3-6 ºC below the boiling point. As the protocol calls for the test to be done with the lid off, the simmering phase will require a somewhat higher power to keep the water close to boiling. The WBT version 3.0 turn-down ratio can thus be defined as the ratio of the stove's *high* power output to its simmer power output.

3.4 Quality Control

For each fuel/stove combination, a series of preliminary experiments were carried out to standardise the burn cycle and minimise the natural variability due to differences in operator behaviour. In order to familiarise the operators with the testing procedure and with the characteristics of the stove, these trial runs were conducted repeatedly until a stable mode of operation was established. Thereafter three definitive tests were conducted for each fuel/stove combination. After each fuel/stove combination was tested, the probes were cleaned and the pumps and machines checked and zeroed.

The sum of the emission factor values of the oxygen-containing carbon gases (CO_2 and CO); represented by [∑Carbon (EF)] is the sum of [CO (EF)] and [CO_2 (EF)]. The total oxygen, represented by [$\sum O_2$ in all gases] can be used as an instrument and data quality check. These, together with the gas pump flow rate, were monitored and recorded (Figure 11). The two ∑ lines (total carbon and total oxygen) should track each other. With low hydrogen fuels they overlap (No consumption of oxygen to form H_2O, a component that was not monitored). Any departures from parallel tracking are indicators of deviant instrument behaviour and reason to discontinue the test or discard a particular data set. On the left axis is the sum of all detected oxygen (expressed as O_2 equivalent) and the sum of the carbon (EF) values. The instantaneous $\sum O_2$ level should be constant if the fuel is burned at a uniform rate and if all the combustion products are detected. The sum of the (EF) values of all oxygen-containing gases will be equal to the background atmospheric oxygen level of 209,480 ppm (plus any O_2 released from the fuel at that time). If the H_2O formed from combustion of any hydrogen in the fuel [H_2O (EF)] is not measured and not included in the calculation, the [$\sum O_2$ EF] value will be low by that amount.

Under poor combustion conditions the *water-shift gas reaction* (a chemical reaction in which carbon monoxide reacts with water vapour to form carbon dioxide and hydrogen) can take place creating additional CO_2 without using any oxygen from the air supply. This CO_2 is detected and the additional oxygen added to the derived [$\sum O_2$]. Basically, this procedure uses an oxygen balance model at the beginning and end of the calculations to detect deviations from the expected values caused by possible instrument or calculation errors.

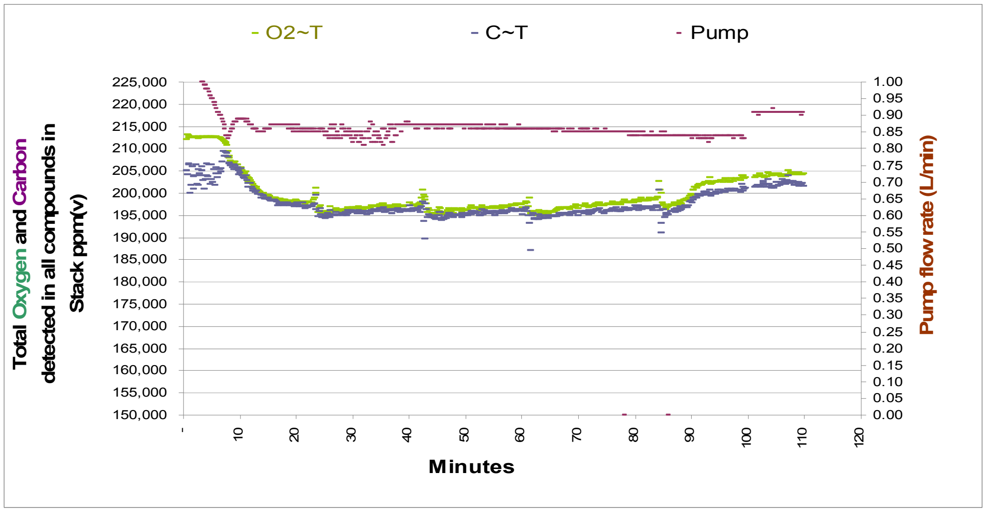


Figure 11: Data quality check: total oxygen, total carbon (EF), and pump flow rate (instrument check)

3.5 Development of Protocols and Standard Operating Procedures

This section addresses the following objective(s):

- To develop a set of testing protocols for the quantification of combustion gas emissions and thermal performance from domestic fuels and cooking devices.
- To document a set of standard operating procedures for all phases of the newly developed test procedure.

The documents are to be designed to meet a number of basic requirements and criteria in protocols and standard operating procedure development. The experimental procedure and related methods and apparatus for thermal and emissions performance of fuel/stove combinations will be incorporated into a protocol document template from the Desert Research Institute, Reno, Nevada. The language and format of this protocol document template will be adhered to in developing alternative stove testing protocols and standard operating procedures. Each page will be created with a heading outlining the following:

- A unique title (abbreviated if desired)
- Date of approval and version number
- The number of the SOP
- Page number and the total number of pages of the SOP
- Revision number.

The first section of the protocols and the standard operating procedures is intended to give a general description of the protocol or the standard operating procedures. Under general description the following sub-sections will be considered: purpose of procedure; measurement principle; measurement interferences and their minimisations; ranges and typical values of measurements; typical low quantifiable limits, precision and accuracy; personal responsibilities; definitions; and related procedures. This section is aimed at presenting an unambiguous instruction for the proper management and administration of the protocol and the standard operating procedures.

For example, this first section gives the reader an explicit overview of the stove testing procedures described in the protocols, including interferences that could result from the use of equipment and resultant errors from the test procedures. Measurement principles of the weighing scales and gas analysers including their ranges of measurements and accuracy must be carefully documented. These are essential for reproducible results as a change in accuracy has the potential to create a bias in the final result.

Other stove testing procedures that directly relate to this protocol must be highlighted. For, example a standard operating procedure for the analysis of emissions using a Testo® flue gas analyser directly relate to the standard operating procedure for the determination of thermal parameters of a fuel/stove combination, and should be stated likewise.

The second section will deal with the instrumentation and the apparatus used in the protocols and the standard operating procedures. In list form, all equipment and supplies required will be recorded in this part of the protocol. Where reagents are made up in the laboratory, the method for the preparation of these will be included, or referred to in a separate protocol. Safety procedures and personal protective equipment will be specified under this section.

The third section will highlight the analysis and quantification of data obtainable using the protocols and the standard operating procedures. A description of how to operate the equipment and how to analyse the experimental data will be included. For example, test procedures described in Section 3.3 are incorporated into the template document from the DRI and are written in the language and format of a protocol document. All the data collected will be reviewed and organised to find out if the hypothesis was supported. The data will be exported into a statistical package (Excel®) for analysis and quality assurance purposes. The Excel® spreadsheet document must able to calculate all stove performance parameters which include thermal efficiency, emissions performance, fuel consumption and the creation of performance curves for each test entered. It is also possible to include a statistical tool for the determination of the critical p-values for the test. Most importantly, the spreadsheet should be able to normalise emission factors for excess air, and to account for the moisture content and differences in the calorific values of the fuel.

The last section of the protocols and standard operating procedures will be designed in a way that data can be validated and for quality control purposes. Quality control is a way to test the accuracy of the procedure performed.

CHAPTER FOUR

This chapter presents and discusses a motivation for the heterogeneous stove testing protocol (HTP) and standard operating procedures. Results from gas emissions from a variety of paraffin, charcoal and coal stoves are presented in detail as examples of how the protocols are applied in practice, and of typical emissions and thermal performance results. Thermal parameter and rated system performance results of three paraffin stoves are presented in some detail. This data is useful for the ranking of fuel/stove combinations. A conceptual comparison of the HTP and the Water Boiling Test Version 3.0 is presented at the end of the chapter.

4. Results and Discussion

Preceding chapters explicitly presented the limitations of existing stove testing protocols for evaluating the performance of fuel/stove combinations. From the critical evaluation of the classical Water Boiling Test method, a need to develop alternative and robust stove testing protocols that are representative of real-world uses of fuel/stove combinations, was established. The proposed protocol is intended to provide substantiation of claims under the CDM projects and voluntary carbon markets, related to stove programmes. In this chapter a report is given on the development of what has been termed the ***H**eterogeneous stove **T**esting **P**rotocol* (*HTP*) for a range of stoves and fuels, including paraffin, coal and charcoal – all fuels in widespread use in Southern Africa. Section 4.1 presents a motivation for the development of the *HTP* and standard operating procedures. The underlining principles behind the development and presentation of stove testing protocols are discussed. An extract of the protocol and standard operating procedure is presented and discussed – the full protocol is contained in the appendices.

Subsequent sections present typical results of emission performance and thermal efficiency of selected paraffin, coal and charcoal burning stoves, as illustrations of the application of the ***H**eterogeneous stove **T**esting **P**rotocol*. A full comparative analysis of a range of liquid and gel fuelled stoves has been presented in technical reports to clients, and is outside the scope of this thesis. These results are used to demonstrate the robustness of the *HTP* relative to existing protocols in the assessment of stoves, namely the Water Boiling Test Version 3.0. A conceptual comparison between the *HTP* and the WBT Version 3.0 is presented in Section 4.6.

A two tailed student T-test at the 95% confidence level is used for statistical evaluation of the thermal and emissions data. Note that for the purposes of this study, a statistically significant number means that the p-value is less than 5% ($p<0.05$); a number that is not statistically significant means that the p-value is greater than 5% ($p>0.05$). Even though gases such as SO_2, H_2S, NO, NO_X, and H_2 can be reported using the *HTP*, only carbon monoxide and carbon dioxide have been chosen as our indicator pollutants and are reported as such in this thesis. Sulphur and nitrogen pollutants are omitted for the following reasons. In South Africa the paraffin available on the market has low sulphur content, thus low emissions of SO_2 and H_2S pollutants were observed for paraffin burning stoves. Temperatures in the flame do not reach near the threshold for NO_X production; consequently there are low NO_X emissions.

4.1 Motivation for the *Heterogeneous Stove Testing Protocol*

The Sustainable Energy Technology and Research (SeTAR) Centre at the University of Johannesburg was formed as part of a national project to develop safer, cleaner burning and more energy efficient domestic stoves to replace the ubiquitous and highly polluting coal braziers and dangerous wick-type paraffin stoves. With many of the new products entering the market displaying novel features, there was the need to augment the South African Bureau of Standards (SABS) tests with a broader view of stove performance, specifically with respect to carbon monoxide emissions of unvented domestic paraffin, ethanol gel fuel, charcoal, and coal stoves. The SeTAR Centre was commissioned to characterise thermal efficiency and gaseous emissions of a batch of liquid fuel and gel stoves. In the process of evaluating these stoves, SeTAR staff were engaged simultaneously in the development of written procedures for testing, and development of spreadsheet calculations[17] that included both primary and secondary combustion effects, leading to the development of what we term the *Heterogeneous stove Testing Protocol* (*HTP*).

The essence of the *HTP* is to test the stove over the full range of design attributes, which cover anticipated domestic use, using two widely available pot sizes. The underlying proposition was that pollutant emissions might vary with power setting, or might change with the altered flow patterns associated with different pot sizes. Accordingly, the new protocol requires that the device is operated, as per manufacturer's instructions or local fire tending practices, over a range of three power settings (*high, medium*, and *low*) to boil water in two representative pot sizes (5 L and 2 L water). Features of the test protocol require triplicate tests under each condition (stove/fuel combination; power setting; pot size) to obtain standard deviations and quality assurance on reproducibility. However, it is important to note that the argument and examples given herein are limited using only CO as the indicator pollutant, whether from paraffin, charcoal or coal stoves; particulate emissions from wood and coal stoves are important for health-based and climate reasons, but are outside the scope of this thesis.

[17] The spreadsheet is available in internal reports at the SeTAR Centre and did not constitute part of the scope of this research work.

We adopt an approach of testing in controlled, replicable laboratory conditions, fuel/stove combinations that are typical of real world use, to perform standardised but representative tasks. This approach separates the intrinsic performance of the fuel/stove combination from the vagaries of real world use. Acknowledging that stoves are, by craft or design, adjusted to local conditions, the protocol explicitly allows for the use of a fuel type, size, moisture content and load for which a device was designed, or as commonly used.

Important to the analysis method is an accurate description of the fuel, both in terms of major elemental composition and the moisture content (wet basis). As fuels vary in composition, even within apparently standard liquid fuels like paraffin, each batch of fuel was analysed for determination of its calorific value prior to testing, using a bomb calorimeter (CAL^{2K} ECO® Calorimeter). During the stove testing procedure standard precautions were taken, such as ensuring a draft free environment (variable heat loss from pot walls can be caused by forced drafts). At the end of each test, data and analysis method are coded into a standard Excel® spreadsheet. The pre-programmed calculations include measures to compensate for changes in boiling point with altitude.

4.1.1 The Heterogeneous stove Testing Protocols (HTP)

The development and documentation of protocols and standard operating procedures is one of the main objectives of this thesis. The presentation and discussion of the protocols developed constitutes one of the products of this research. The following is a presentation and discussion of the *HTP* with specific emphasis on the standard operating procedures.

The *HTP* was developed and documented as a complete set of *standard operating procedures* (SOPs), given in full in the Appendices. Separate SOPs are presented for the determination of (i) thermal and emissions performance of fuel/stove combinations; and (ii) the operation of the Testo® flue gas analyser. The *HTP* SOPs were designed to meet a number of basic requirements and criteria in protocols and standard operating procedure development, based on a template adopted from the Desert Research Institute (DRI), Reno, Nevada. Each page was created with a heading outlining the following: unique title (abbreviated if desired); date of approval and version number of the SOP; page number and the total number of pages of the SOP; and revision number (Figure 12). The inclusion of the date and revision numbers of the SOP is important for linking a particular version of the SOP to a particular set of test results. This is an important discipline in testing and any deviations from the SOP should be noted in the experimental log books.

The first section of standard operating procedures was intended to give a general description of the protocol or the standard operating procedures. It describes the purpose of the process or procedure; organisation or regulatory requirements; and limits to the use of the procedure. Sets of observations that reduce uncertainty where the result is expressed as a quantity are indicated and the measurement interferences and their minimisation highlighted. A typical example of this section is shown in the following extract (Figure 13):

UJ SeTAR CENTER STANDARD OPERATING PROCEDURE		Page:	8 of 12
Title:	The heterogeneous testing procedure for thermal performance and trace gas emissions	Date:	15 Dec 2010
		Number:	1.05
		Revision:	2

Figure 12: Section from the *HTP* showing the heading of the SOP

UJ SeTAR CENTER STANDARD OPERATING PROCEDURE		Page:	2 of 13
Title:	The heterogeneous testing procedure for thermal performance and trace gas emissions	Date:	15 Dec 2010
		Number:	1.05
		Revision:	2

1 GENERAL DISCUSSION

1.1 Purpose of Procedure

This standard operating procedure is intended to:

- Provide a basic understanding of the principles of stove testing.
- Describe routine operation of stove emissions performance and stove efficiency performance.
- To codify actions which are taken to determine the thermal and emissions performance of fuel/stove combinations.
- Detail quality control procedures for the reproduction of results in different tests under the same operating conditions.

This procedure is to be followed by all staff and analysts at the SeTAR Centre, University of Johannesburg.

1.2 Measurement Principle

Procedure uses mass loss and temperature gain for the determination of thermal efficiency.

TESTO® XL 350/454 uses electrochemical cells for gas measurements. CO_2 is determined using a non-dispersive infra red cell and is normally depicted as CO_2 IR. Oxygen balance is used for the calculation of excess air.

Figure 13: A typical section from the *HTP* showing the scope and limitations of the SOP

Criteria for good writing practice in preparing SOPs require concise, step-by-step instructions in an easy to read format. Sentences should be in the form of commands and thus are easy to understand (Figure 14 & Appendix A). Long sentences create a 'weighty effect' on the reader and need to be read slowly and carefully. Long sentences are good when a reader has time to think. In SOPs, long sentences tend to include more than one step and hinder understanding of operational sequences.

UJ SeTAR CENTER STANDARD OPERATING PROCEDURE		Page:	9 of 13
Title:	The heterogeneous testing procedure for thermal performance and trace gas emissions	Date:	15 Dec 2010
		Number:	1.05
		Revision:	2

4.2 Experimental procedure

4.2.1 Weigh the insulation material between the scale and the stove

4.2.2 Weigh the empty pot and lid

4.2.3 Put 5.000 Litres or 2.000 litres of water into the pot, weigh everything (Pot + Lid + water). Alternatively fill the pot to 80% of capacity and weigh the combination and record all.

4.2.4 Measure the temperature of the water by placing the plastic frame holding the thermocouple into the water, 50 mm above the bottom of the pot in the centre of its diameter.

4.2.5 Weigh the stove without the fuel and record the mass on the data sheet.

4.2.6 Weigh the fuel that will be used during the test and place it on the scale next to the stove. If it is a liquid fuel stove skip this step.

4.2.7 Fill the stove with the fuel. Measure and record the initial temperature of the fuel before lighting it up. Weigh the stove and the fuel and record the mass in the data sheet. There should be no spilled fuel on the stove that will evaporate and affect the total weight.

4.2.8 Choose an appropriately sized scale. Press ZERO to set the mass reading to 0.000 kg or 0 grammes.

4.2.9 Place the stove on the scale. It should show the mass of the stove + fuel (M0~0)

Figure 14: Typical section of the *Heterogeneous stove Testing Protocols* (HTP)

Personal responsibilities should be explicitly defined to ensure that the procedures are carefully followed. It is the duty of the *Laboratory Manager* to ensure that the procedures are followed in a manner that does not pose a danger to personnel and machinery. Most importantly, related SOPS that directly speak to the existing SOP must be stated likewise so that they can be read and revised in conjunction with the SOP in question. An extract from the *HTP* demonstrates these main aspects in SOP development and documentation (Figure 15).

The DRI template was not modified during the documentation of our *HTP* protocols and care was given in filling all the relevant sections. Where information was not available due to the nature of the procedure, this was indicated as such. The language was adopted and adhered to throughout the development and documentation process. These protocols were then used to carry out comparative thermal and emissions performance evaluation of selected paraffin, charcoal and coal stoves described in the following sections.

1.6 Personal Responsibilities

All technicians in the laboratory carrying out this procedure are responsible for carefully reading and understanding the entire operating procedure before performing the tasks. They are also responsible for setting up for source sampling, the TESTO® XL 350/454, changing filters, un-installing equipment once testing is complete, cleaning, maintenance and calibration of instrumentation, and coding and analysing data on an EXCEL® spread sheet. The Laboratory Manager is responsible for ensuring that the procedures are properly followed and to deliver the samples for shipping or for testing in the laboratory within the specified time period.

1.7 Definitions

No terms used in this procedure require definitions

1.8 Related procedures

SOPs related to stove testing procedures which should be read and revised in conjunction with this document are:

- SeTAR SOP # 2.05 Analysis of combustion trace gases using a TESTO® XL 350/454 analyser
- SeTAR SOP # 3.0 Calibration of TESTO® XL 350/454.

Figure 15: Extract from the *HTP* showing personal responsibilities and related procedures

4.2 Gas Emissions from Paraffin Burning Stoves

The effects of different pot sizes on the emissions performance of three paraffin fuelled stoves were investigated. Table 5 gives the mass emission factors in grammes per kilogramme of fuel burned when using the baseline paraffin wick stove. Tests were carried out using two pot sizes (2 litre water and 5 litre water) and an average of the three tests is given together with the standard deviation.

The results showed that there is no significant difference at the 95% confidence level, using a two-tailed student T-test, in CO emissions produced at the same power setting as the user switches between pot sizes (6 L and 3 L). This shows that the pot sizes used in these tests may not affect the combustion characteristics of all the three paraffin stoves tested (Table 5, Table 6 and Table 7). This result is similar to that of Bhattacharya *et al*. (2002) who found that the size of the pot did not affect the efficiency of the stoves tested.

However, the CO emissions change significantly ($p<0.05$) using different pot sizes, between *high*, *medium* and *low* power settings for some of the stoves tested. For the baseline paraffin stove there is a significant difference ($p<0.05$) in CO emissions produced by the stove between the *high* and the *medium* power setting when using a small pot with CO emissions increasing from 49 g kg^{-1} to 93 g kg^{-1} from a *high* to a *medium* power setting (Table 5). As the stove is turned down to the *low* power setting, even lower CO emissions are recorded resulting in a significant difference ($p<0.05$)

between the *medium* and *low* power settings (Table 5). The large pot case shows a constant increase in CO emissions produced by the stove as the user turns down the stove from a *high* power setting to *low* power setting. However, there is no significant difference ($p>0.05$) in CO emissions produced across a range of power settings. The increasing nature of the CO appears to be due to a lowering of the gas phase reaction caused by low flame temperatures and reduced fire-power at lower power settings. Lower temperatures inside the stove promote incomplete combustion so that more amounts of products of incomplete combustion are produced.

Table 5: Gas emission factors (mass) for the baseline paraffin wick stove (Stove A) tested across full range of power setting using two pot sizes

		Baseline Paraffin Stove				Statistical Analysis			
		Mass Emission Factors [g Gas kg^{-1} Fuel]		Mass Emission Factors [g Gas kg^{-1} Fuel]		Large pot against small pot at same power setting			
Gas	**Power Setting**	**Small Pot (Avg ± STD) (N = 3)**	**CoV**	**Large Pot (Avg ± STD) (N = 3)**	**CoV**	**% difference**	**t-test**	**p-Value**	**Sig @ 95%**
CO_2	High	3 059 ± 13	0.00	3 047 ± 28	0.01	-0.4%	-0.73	0.51	No
	Medium	2 985 ± 50	0.02	3 023 ± 36	0.01	1.3%	1.14	0.32	No
	Low	3 096 ± 50	0.02	3 010 ± 57	0.02	-2.8%	-2.01	0.12	No
CO	High	49 ± 8	0.24	57 ± 16	0.29	15%	0.73	0.51	No
	Medium	93 ± 27	0.44	71 ± 21	0.30	-24%	-1.14	0.32	No
	Low	27 ± 26	0.52	79 ± 34	0.43	184%	2.01	0.12	No

From this illustrative example it can be shown that the power setting has the potential to influence the CO emissions of the baseline paraffin wick stove regardless of the pot size used. This suggests that fuel/stove combinations need to be assessed for emissions performance across a range of conditions (e.g. power setting), if thermal efficient and less polluting stoves are to be designed and disseminated.

The effect of pot size on gaseous emission factors was also investigated for the new type paraffin wick stove (Table 6). An average of the three tests carried is presented together with the standard deviation. Statistical analysis results from a two tailed student t-test, showing p-values at the 95% confidence level are presented in Table 6.

The results showed that, when using a small pot case, there is a significant difference ($p<0.05$) in the CO emissions produced by the stove as the user adjusts the stove from the *high* to the *medium* power setting. However, there is no significant difference ($p>0.05$) in CO emissions between the *medium* and the *low* power setting (Table 6). This is because the *low* power setting is less stable and more indicative rather than exact. The large pot case does not report any significant differences in the CO emissions produced as the user switches between power settings. The stove shows an increase in emissions of CO as the user turns down the stove from a *high* power through to a *low* power setting. This is due to reduced fire-power and flame temperatures at *low* power settings, as explained above.

Table 6: Gas emission factors (mass) for the new type paraffin wick stove tested across full range of power setting using two pot sizes

		New type Paraffin Stove				Statistical Analysis			
		Mass Emission Factors [g Gas kg^{-1} Fuel]		Mass Emission Factors [g Gas kg^{-1} Fuel]		Large pot against small pot at same power setting			
Gas	**Power Setting**	**Small Pot (Mean ± STD) (N = 3)**	**CoV**	**Large Pot (Mean ± STD) (N = 3)**	**CoV**	**% difference**	**t-test**	**p-Value**	**Sig @ 95%**
CO_2	High	3 060 ± 16	0.01	3 055 ± 12	0.00	-0.1%	-0.36	0.74	No
	Medium	2 990 ± 32	0.01	3 004 ± 51	0.02	0.5%	0.41	0.70	No
	Low	3 064 ± 59	0.02	2 932 ± 11	0.04	-4.3%	-1.82	0.14	No
CO	High	49 ± 9	0.19	58 ± 7	0.14	5.0%	0.36	0.74	No
	Medium	91 ± 19	0.21	82 ± 30	0.32	-9.0%	-0.41	0.70	No
	Low	50 ± 35	0.74	124 ± 65	0.52	166%	1.82	0.14	No

The effect of pot size was also investigated for the pressurised paraffin stove and the results of gaseous emissions factors presented in Table 7. An average of the three tests is given together with the standard deviation. Statistical analyses results from a two tailed student t-test, showing p-values at the 95% confidence level are also presented.

Results show that that there is no significant difference ($p>0.05$) in emissions of CO produced at the same power setting as the user switches between pot sizes. Emissions of CO remained constant across a range of power settings for both the small and the large pot (Table 7). This is due to the combustion mechanism of the stove which is not affected by air movements around the base of the pot. This indicates that power setting does not seem to affect the production of emissions of CO in the pressurised paraffin stove.

The pressurised paraffin wick stove produced low CO emissions compared to the baseline paraffin wick stove (Table 5) and the new type paraffin wick stove (Table 6). CO emissions per task accomplished are compared for the three paraffin stoves in the following section.

Table 7: Gas emission factors (mass) for the pressurised paraffin stove tested across full range of power setting using two pot sizes

		Pressurised Paraffin Stove				Statistical Analysis			
		Mass Emission Factors [g Gas kg^{-1} Fuel]		Mass Emission Factors [g Gas kg^{-1} Fuel]		Large pot against small pot at same power setting			
Gas	Power Setting	Small Pot (Mean ± STD) (3 tests)	CoV	Large Pot (Mean ± STD) (3 tests)	CoV	% difference	t-test	p-Value	Sig @ 95%
CO_2	High	3 140 ± 2	0.006	3 139 ± 5	0.0016	-0.05%	-0.53	0.62	No
	Medium	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	Low	3 138 ± 3	0.001	3 139 ± 4	0.0013	0.02%	0.23	0.83	No
CO	High	1.3 ± 1.0	0.82	2.3 ± 2.9	1.27	71%	0.53	0.62	No
	Medium	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	Low	2.9 ± 2.0	0.70	2.4 ± 2.0	1.01	-15%	-0.23	0.83	No

n/a indicates that tests were not carried out at this power setting. The pressurised paraffin stove had a *high* power setting and a *low* power setting only, thus no tests were carried out on the *medium* power setting.

4.2.1 CO emissions per task accomplished compared

The CO emissions per task accomplished were investigated for the three paraffin stoves, using the *Heterogeneous stove Testing Protocol*. This section presents results on CO emissions produced, in grams per litre of water boiled (g L^{-1}) (as defined in Chapter 3 referring to an 80°C rise in temperature). Mean and standard deviation values were derived from three successful experiments for each of the fuel/stove combinations.

The difference between the emissions of CO of small and large pots was not statistically significant ($p>0.05$), for all three stoves tested (Figure 16). The baseline paraffin wick stove gave a task specific CO emission of 0.83 ± 0.17 g L^{-1} when using a small pot, and 0.78 ± 0.24 g L^{-1} when using a large pot (Figure 16). The new type paraffin wick stove showed a task specific CO emission of 0.94 ± 0.20 g L^{-1} (for small pot) and 0.76 ± 0.10 g L^{-1} when using the large pot. However, the difference between the two stoves is not statistically significant ($p>0.05$) for both pot sizes.

The pressurised paraffin stove showed significantly lower task specific CO emissions of 0.03 ± 0.02 g L^{-1} using a small pot, compared to the two wick stoves (Figure 16). This can be explained by the operating nature of the burner which vaporises the paraffin as it passes through the heated nozzle. The nozzle then sends a stream of this vaporised paraffin vertically to the chamfered underside of the copper head. The vapour mixes well with the air, allowing for a more complete combustion. In addition, as the burner on the pressurised stove inducts air into the fuel jet it is less influenced by air flow around the bottom of the pot, resulting in low emissions of products of incomplete combustion. CO is formed when the fuel and air are not completely mixed - complete mixing does not usually occur in stoves without controlled drafts of air, a well known performance feature of wick type stoves.

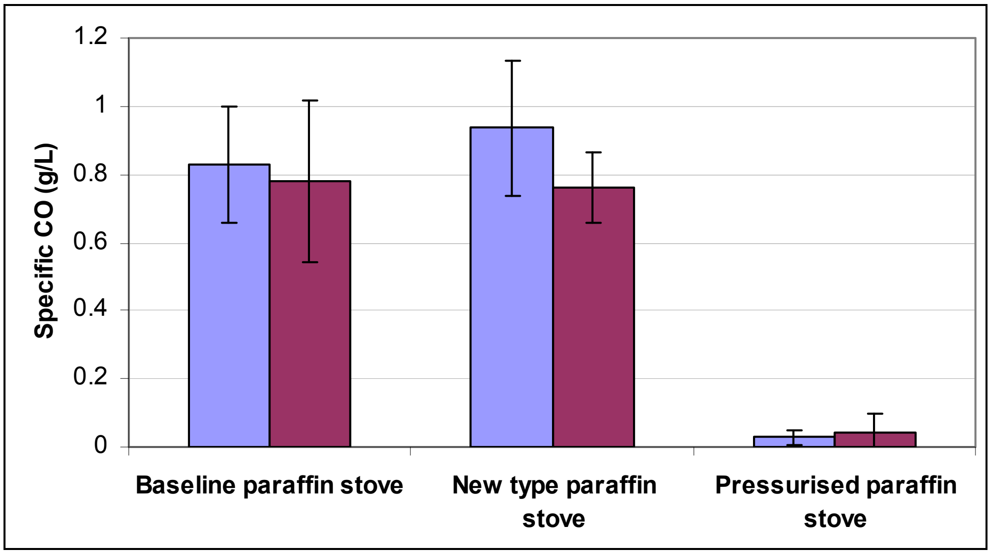


Figure 16: Specific CO (g L^{-1}) for two paraffin wick stoves, and one pressurised paraffin stove using small and large pots

Results from this study showed that the new type paraffin wick stove shows no improvement on the baseline with regard to CO emissions. However, the stove has additional safety features which contributed to the device passing the national standards for paraffin flame based appliances (SANS 1906:2009).

4.3 System Performance of Paraffin Burning Stoves

In this section, system performance parameters are compared for the three selected paraffin fuelled stoves, using the *HTP*. The parameters to be evaluated are: burn rate, fire-power, turn down ratio, thermal efficiency, combustion efficiency ($CO:CO_2$ ratio) and specific fuel consumption. The system performance can be divided into two categories: (stove) rated performance (which assumes steady state conditions); and task based (which is time based). The $CO:CO_2$ ratio is included here because: (i) it is an indicator of incompleteness of combustion; (ii) of health safety issues; and (iii) of atmospheric chemistry interest. The following sections present separate analyses of the system performance of the baseline and the new type paraffin wick stove, and the pressurised paraffin stove, followed by a comparative analysis of the three.

4.3.1 System performance of a baseline paraffin wick stove

The baseline paraffin stove does not give a clear indication for setting power levels. The fire-power of the stove is determined by the moving the wick up or down. According to Bradnum (2007), the controller on the device does not give a clear indication for setting the wick up or down, although this becomes obvious with repeated use of the device. When adjusting the controller, turning it clockwise sets the wick up and anticlockwise sets it down. The *high* power setting is achieved by turning the controller clockwise to its physical limit. However, with the *low* power setting turning the controller anticlockwise to its physical limit results in the flame going out. The *low* power setting is kept at the lowest level that keeps the flame going and stable. The *medium* power setting is mid-range between the *high* and the *low* power setting. This *medium* setting is difficult to reproduce during testing since control levels are continuous and not discrete, resulting in a greater variability in the data obtained at this setting.

The system performance results for the baseline paraffin wick stove, obtained following the *HTP*, are summarised in Table 8.

Table 8: System performance of the baseline paraffin wick stove across different power settings

Parameter	Power Setting	Large Pot (Mean ± STD) (N = 3)	Small Pot (Mean ± STD) (N = 3)	Statistical analysis: % difference between large and small pot	t-test value (DF=4)	p-value	Sig @ 95%
Fuel Burn Rate [g hr^{-1}]	High	108 ± 9	113 ± 9	4%	0.64	0.56	No
	Medium	89 ± 21	88 ± 16	-1%	-0.07	0.95	No
	Low	69 ± 12	46 ± 8	-50%	-2.77	0.05	No
Fire-power [Watts]	High	1 320 ± 110	1 376 ± 105	4%	0.64	0.56	No
	Medium	1 089 ± 259	1 077 ± 198	-1%	-0.07	0.95	No
	Low	843 ± 150	562 ± 92	-33%	-2.77	0.05	No
Thermal Efficiency [%]	High	60 ± 1.1	54 ± 1.5	-11%	-5.80	0.004	Yes
	Medium	49 ± 1.8	49 ± 3.6	1%	0.06	0.95	No
	Low	41 ± 6.0	36 ± 2.0	-14%	-1.33	0.26	No
$CO:CO_2$ Ratio [%]	High	5.4 ± 1.6	4.6 ± 0.7	-16%	-0.73	0.50	No
	Medium	6.7 ± 2.1	9.0 ± 2.8	26%	1.15	0.32	No
	Low	7.5 ± 3.4	2.6 ± 2.7	-190%	-1.99	0.12	No
Turn Down Ratio (Fire-power High: Fire-power Low)		1.57 ± 0.31	2.45 ± 0.44				

Fire-power and burn rate: The maximum power of the stove is ~1.3 kW. There is a monotonic increase in fire-power from the *low* to the *high* power setting, indicating that the control mechanism is controlling the fuel burn rate. Greater variability in the fire-power is recorded at the *medium* power setting (Figure 17), because this is not a discrete setting unlike at the *high* power where the control lever is pushed against its physical limit.

The combined (large pot and small pot) **turn-down ratio** is ~2.0 (Table 8). For the large pot case, the baseline paraffin wick stove shows a turn down ratio of 2.45 ± 0.44 (Table 8). When using a small pot size the turn down ratio is reduced by a factor of 1.5 to 1.57 ± 0.31. The difference between the two cases may be due to the difficulty in the control and stability of *low* power setting. Most importantly, these *turn-down ratio* values are defined and calculated differently from the ones obtained when employing the WBT, and so direct comparison should not be made, despite the same common language terminology being used.

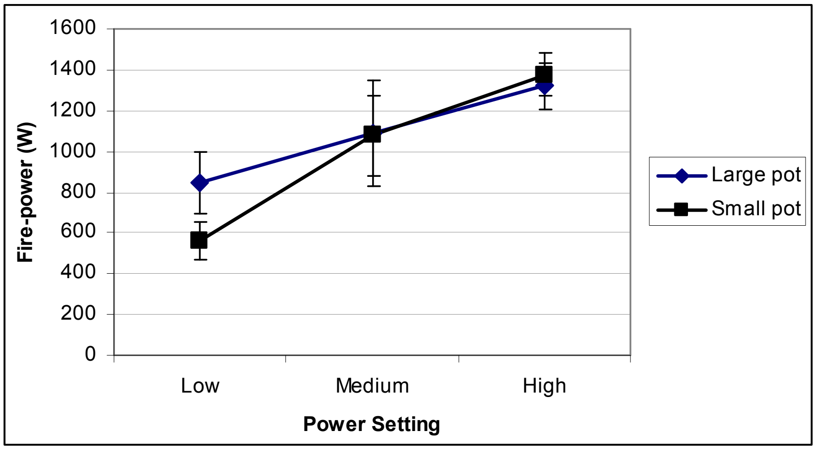


Figure 17: Relationship between fire-power (W) and power setting of the baseline paraffin wick stove

Thermal efficiency: A monotonically increasing relationship is displayed between the fire-power and thermal efficiency (i.e. thermal efficiency values increase from the *low* to the *high* power setting) of the baseline paraffin wick stove using both pot sizes (Figure 18). This is because at the *low* power settings the stove takes longer to heat the water over a specified range. Hence there is a longer time for radiation and convective heat losses from the sides and top of the pot, resulting in a lower efficiency.

There is a statistically significant difference ($p<0.05$) in thermal efficiency at the *high* power setting as the user switches between pot sizes (Table 8). This shows that pot size has the potential to affect the system efficiency, at the *high* power setting. For the *medium* and *low* settings, the differences in thermal efficiency for large and small pots are not statistically significant ($p> 0.05$).

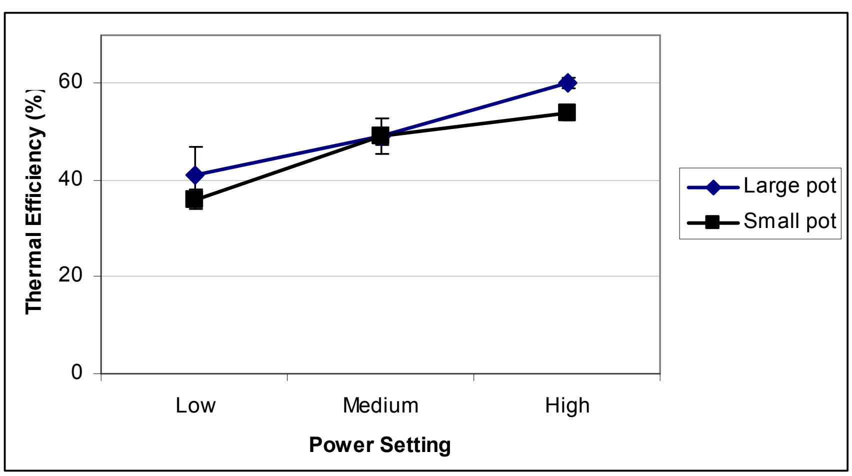


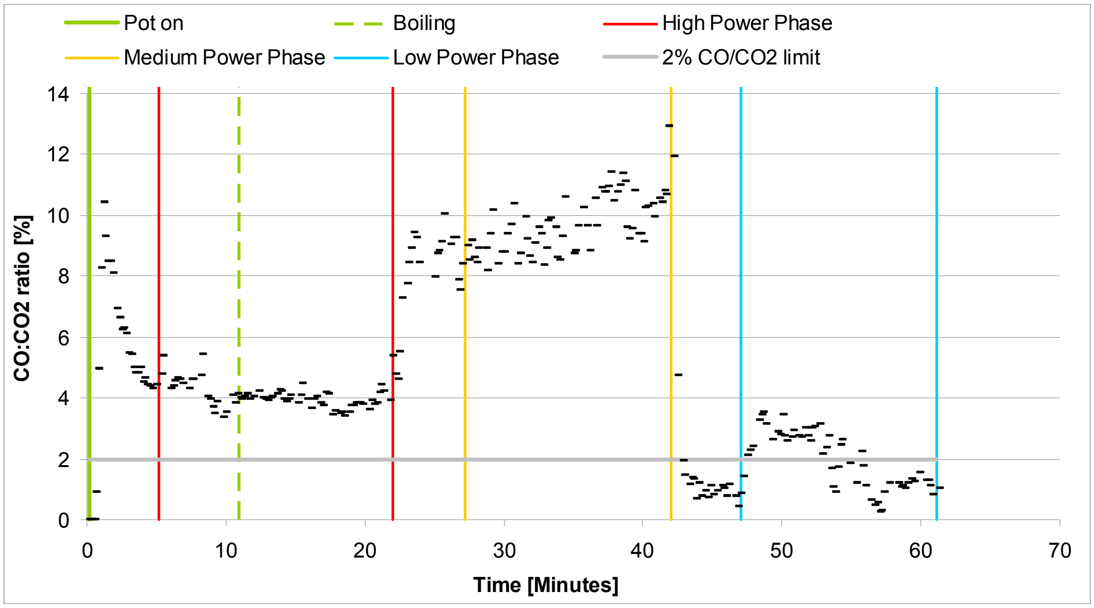
Figure 18: Relationship between thermal efficiency (%) and power setting for the baseline paraffin wick stove

Combustion efficiency (indicated by the $CO:CO_2$ ratio): The baseline paraffin wick stove showed that there was no statistically significant difference ($p>0.05$) in the calculated $CO:CO_2$ ratio (Table 8) as pot sizes are varied. However, differences in the $CO:CO_2$ ratio can be seen between power settings for the same pot with a monotonic relationship for the large pot, and a maximum $CO:CO_2$ at *medium* power for the small pot. For the small pot case, there is no significant difference at the 95% confidence level (t-value = -2.65, p-value = 0.12) between the *high* and the *medium* power settings. There is a marginal statistically significant difference (t-value = 2.78, p-value = 0.045) between the *medium* and the *low* power setting. There is no statistically significant difference (t-value = 1.26, p-value = 0.34) in the $CO:CO_2$ ratio between the *low* and the *high* power setting. For the large pot case, there is no statistically significant difference ($p>0.05$) in the $CO:CO_2$ ratio across the range of power settings. Overall, we conclude that for the baseline paraffin wick stove, neither the power setting nor the pot size significantly affects the combustion efficiency. However, the average $CO:CO_2$ ratio (6.0±5.8%) is well above the 2% limit contained in the SABS SANS 1906:2009 for emissions from domestic paraffin stoves.

Presented in this thesis is the first systematic batch of test results of a set of liquid and charcoal stoves. As such, the central features of the results will be highlighted, rather than attempting to explain every anomaly in the performance curves. These curves enable us to understand when a result shows deviant behaviour, and further systematic testing to understand the causes of variability in the results will be carried out at the SeTAR laboratory. These tests indicate the necessity to conduct replicated tests on the stoves, as single tests could yield unrepresentative results with no warning of deviant behaviour. The possibility of such variability in evaluation of stoves *as received* is one of the main characteristics which our test procedure intends to uncover.

For the small pot case, the $CO:CO_2$ ratio (a measure of combustion efficiency), was well above the SANS limit of 2% for *high* and *medium* power settings, and varying around to the 2% limit for *low* power setting.

The type of profile shown in Figure 19 is missed if one employs the WBT, which does not generate performance curves over a range of power settings and pot sizes. These performance curves are important in that they can reveal design weaknesses and strengths of the device at different power settings across a range of conditions. Under real life conditions, stoves are not only used at *high* power setting. Stoves are used for simmering food (*medium* power), for keeping the food warm (*low* power), and for space heating (*low* power). These results are significant for stove design purposes in that they can optimise the efficiency of the stove while using a pot size appropriate to the stove across a range of conditions.



(High power – time to boil; low and medium power – time to increase water temperature to 70°C)

Figure 19: Combustion efficiency profile for the baseline paraffin wick stove using a small pot

Pot size: The effect of pot size was assessed across a range of power settings, for the baseline paraffin wick stove. Table 8 shows that the **fire-power** of the baseline paraffin wick stove is not affected by the size of the pot. There was found to be a significant difference ($p<0.05$) in **thermal efficiency** of the stove at *high* power setting as the user varied pot sizes. This shows that pot size has the potential to affect thermal efficiency of the baseline paraffin stove, only at the *high* power setting (Table 8). There was no statistically significant difference ($p>0.05$) in **combustion efficiency** between the pot sizes over a range of power settings.

4.3.2 System performance of the new type paraffin wick stove

The controller of the new type paraffin wick stove is connected to an external lever. The lever relies on a friction traction mechanism to function properly. If the stove is tilted or moved slightly, the lever triggers, causing the wick to retract and the top metal cap to close the top of the stove, shutting it down instantly. When adjusting the controller, turning it clockwise and resting it on the lever sets the wick and the top metal cap up, while an anticlockwise movement sets both down. The *high* power setting is achieved by turning the controller clockwise to its physical limit and is easier to reproduce than the *low* and *medium* power settings. A *low* power setting is achieved when the controller is turned anticlockwise. The *low* power setting is kept at the lowest level that keeps the flame alive and stable. The *medium* power setting is mid-range between the *high* and the *low* power setting. This setting is difficult to reproduce during testing since it is not a click setting.

The rated system performance of the new type paraffin wick stove, obtained following the *HTP*, are summarised in Table 9.

Table 9: System performance of the new type paraffin wick stove across different power settings

Parameter	Power Setting	Large Pot (Mean ± STD) (N = 3)	Small Pot (Mean ± STD) (N = 3)	Statistical analysis: % difference between large and small pot	t-test (DF=4)	p-value	Sig @ 95%
Fuel Burn Rate [g hr^{-1}]	**High**	86 ± 0.5	85 ± 4.0	-1%	-0.43	0.71	No
	Medium	67 ± 9.9	58 ± 13.9	-14%	-0.81	0.46	No
	Low	51 ± 21.2	22 ± 6.3	-133%	-2.28	0.09	No
Fire-power [Watts]	**High**	1 046 ± 6	1 034 ± 49	-1%	-0.43	0.71	No
	Medium	817 ± 121	719 ± 170	-12%	-0.81	0.46	No
	Low	624 ± 259	268 ± 77	-57%	-2.28	0.09	No
Thermal Efficiency [%]	**High**	53 ± 1.0	46 ± 1.0	-16%	-9.36	0.001	Yes
	Medium	38 ± 5.2	30 ± 4.9	-25%	-1.87	0.14	No
	Low	21 ± 9.1	20 ± 9.7	-0.4%	-0.01	0.99	No
$CO:CO_2$ Ratio [%]	**High**	4.8 ± 0.7	4.6 ± 0.9	-5%	-0.36	0.74	No
	Medium	7.9 ± 3.1	8.7 ± 1.9	10%	0.40	0.71	No
	Low	12.3 ± 6.9	4.4 ± 3.3	-180%	-1.80	0.15	No
Turn Down Ratio (Fire Power High: Fire Power Low)		1.68 ± 0.70	3.86 ± 1.12				

Fire-power and burn rate: The new type paraffin wick stove gave a fire-power of ~1 kW on *high*. Fire-power increases monotonically from *low* to *high* power (Figure 20). Analogous to the baseline paraffin stove, the new type paraffin stove shows a greater variability at the *medium* and the *low* power settings. This stove shows a profile similar to that exhibited by the baseline paraffin stove (Figure 17).

When using a small pot, the new type paraffin wick shows a turn down ratio of 3.86 ± 1.12 (Table 9). The turn down ratio indicates the degree to which power output from the stove can be controlled by the user. The intent of this metric is to report the amount of control the user has over available heats. This means that a stove with a high turn-down ratio indicates a degree of controllability that often results in a better fuel economy than a stove with a low turn-down ratio. A turn down ratio of one indicates that a stove can not be turned down for simmering.

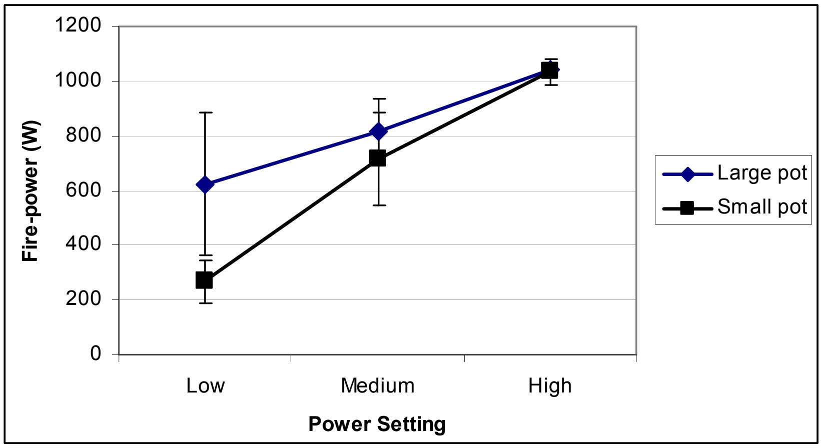


Figure 20: Firepower (W) versus power setting for the new type paraffin wick stove

Thermal efficiency: As with the baseline paraffin stove, thermal efficiency increases monotonically from the *low* to the *high* power setting, for both pot sizes (Figure 21). There is a monotonically increasing thermal efficiency with power setting for the new type paraffin wick stove, for the same reasons.

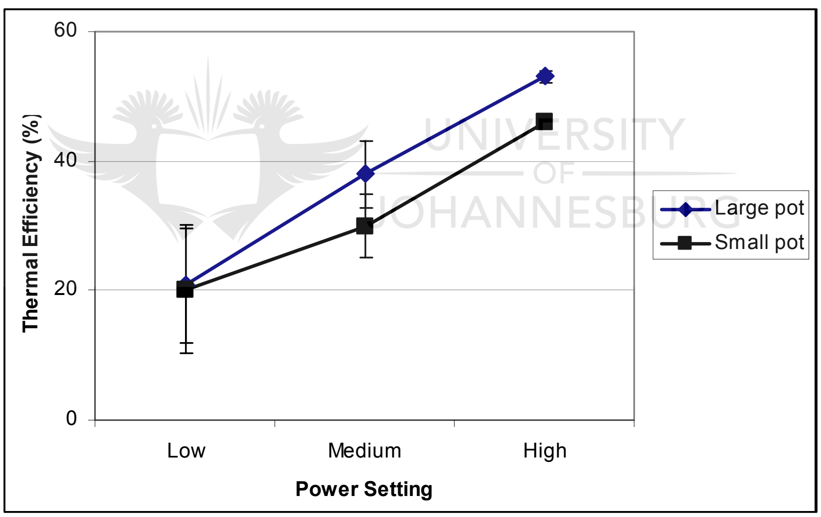


Figure 21: Relationship between thermal efficiency (%) and power setting for the new type paraffin wick stove

Combustion efficiency: There is no statistically significant difference ($p>0.05$) in the calculated $CO:CO_2$ ratio (Table 9) as the user varied pot sizes over a range of power settings. For a small pot case, significant differences at the 95% confidence level (t-value = -3.38, p-value = 0.042) in the $CO:CO_2$ ratio can only be seen between the *high* and *medium* power setting. For the large pot case, there is no significant difference ($p>0.05$) in the $CO:CO_2$ ratio across a range of power settings.

Pot size: Effect of pot size on the performance of the new type paraffin wick stove was assessed. Table 9 shows that **fire-power** of this device is not affected by the size of the pot. There was found to be a significant difference ($p<0.05$) in **thermal efficiency** of the stove at *high* power setting as the user varied pot sizes. This shows that pot size has the potential to affect thermal efficiency of the baseline paraffin stove, only at the *high* power setting. With regards to **combustion efficiency,** when adjusted to *medium* and *low* power settings, the $CO:CO_2$ rose dramatically (depending on pot size). It would appear that the incompleteness of combustion was due not to a shortage of primary air, but potentially to quenching associated with the very narrow gap between the top of the stove and the bottom of the pot − there was notable emissions reduction when a small pot was used.

When using a small pot, the stove shows a remarkably clean burn on *low* power setting. As the stove is turned up to the *medium* power setting, the combustion efficiency worsens but improves slightly on *high* power setting (Figure 22). The large pot case shows a much greater variance at a *low* power setting. The combustion efficiency improves as the stove is turned up to *high* power setting (Table 9). However, there is no simple or *a priori* explanation why the $CO:CO_2$ should vary with a pot size. Combustion efficiency of a stove depends on the wick configuration and the primary air flow, or whether the pot was too close to the flame leading to *quenching*. During the design phase, it would be useful to highlight these design defects so that corrective measures can be taken before the stove is manufactured at scale.

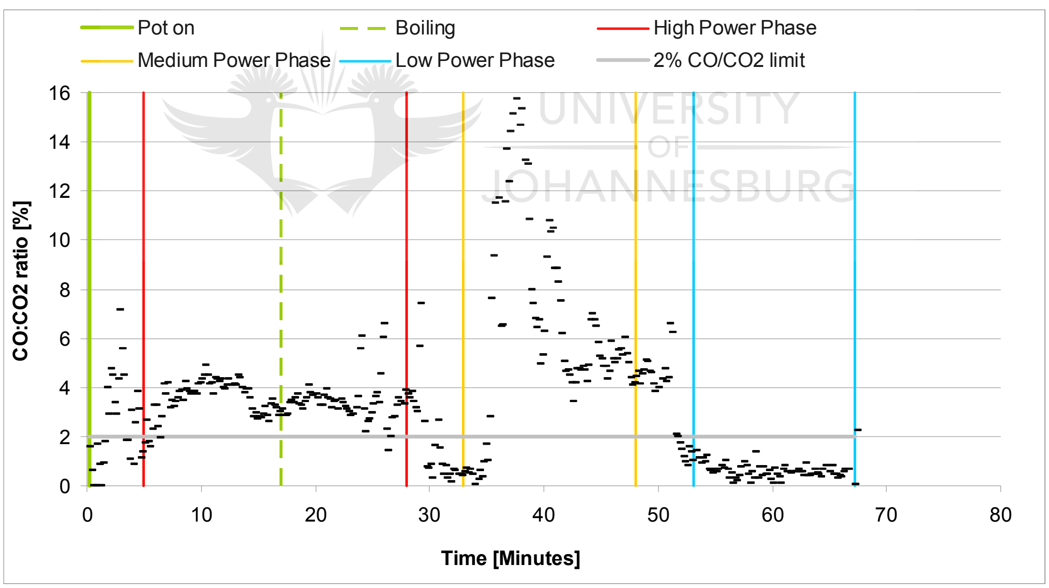


Figure 22: Combustion efficiency profile of the new paraffin wick stove using a small pot

4.3.3 System performance of the pressurised paraffin stove

The pressurised paraffin stove is controlled by means of pressure and release. A rubber ball hand pump is used to generate greater pressure for a larger flame and increased fire-power. The pressure release valve is used to reduce pressure, which leads to reduced fire-power. According to Bradnum (2007), the roaring (jet like) sound of the device can also be used as a form of fire-power control. "*Once the user is familiar with this alarming noise the user can adjust stove settings according to this sound*" (Bradnum, 2007:101).

The method of stove control below *high* power meant that only a single lower power setting was chosen for testing. The stove does not have a pressure gauge indicator for the determination of the *medium* power setting in a reproducible manner. Thus the *medium* power setting was neglected during the tests. The stove was lit with methylated spirit in accordance with the manufacturer's instructions. During testing the nozzle blocked and was cleaned with the provided tool. Two stoves were provided for testing and both exhibited the nozzle blocking problem, with the better performing of the two used for these test results.

The rated system performance of the pressurised paraffin wick stove is summarised in Table 10. Performance of this stove was substantially reduced by the progressive blocking of the nozzle with carbon particles. Over a 15-20 minute period the flame would reduce in size and intensity but combustion appeared to remain relatively good.

The drop off in performance resulted in the stove test reporting a maximum **fire-power** of only 800-850 W at a *high* power setting, and a thermal efficiency of 35-41% (Table 10). The pressurised paraffin stove falls short of the SABS requisite which states that a stove should give a power output of at least 1 kW on *high* (SANS 1906:2006). Fire-power of pressurised stoves can be increased by increasing the diameter of the nozzles. The theoretical relationship between pressure, nozzle diameter and power output depends largely on the square root of the differential pressure and a temperature component (Floor & van der Plas, 1992). The differences in pressure and temperature at both the *high* power setting and the *low* power setting are important in the design of a suitable nozzle diameter for the stove. The WBT may not be able to address this design aspect if tests are run only at the *high* or *low* power setting.

Even with the nozzle blocking problem, the stove emissions were excellent across all power settings and pot sizes, due to the pressurised operation of the stove. The stove shows a similar profile for both **pot sizes**. It gave a $CO:CO_2$ ratio (**combustion efficiency**) of below 1% over a full range of power settings (Figure 23). This is an expected attribute of pressurised stoves which are less influenced by air flow around the bottom of the pot.

Despite good combustion efficiency there are other design factors that need to be integrated into the stove design to maximise its thermal performance. Of note is that two stoves were provided for testing, with both exhibiting the nozzle blocking problem. This is a critical performance issue that requires further investigation.[18]

[18] The manufacturer of the stove, in further discussions, indicated that the issue of nozzle blocking had been addressed in subsequent designs. However, the improved version of the stove was not available in time to be re-evaluated for this thesis.

Table 10: System performance of the pressurised paraffin stove across different power settings

Parameter	Power Setting	Large Pot (Mean ± STD) (N = 3)	Small Pot (Mean ± STD) (N = 3)	Statistical analysis: % difference between large and small pot	t-test (DF=4)	p-value	Sig @ 95%
Fuel Burn Rate [g hr^{-1}]	High	65 ± 4.5	63 ± 5.7	-3%	-0.43	0.69	No
	Medium	n/a	n/a	n/a	n/a	n/a	n/a
	Low	37 ± 5.9	42 ± 4.9	11%	1.06	0.35	No
Fire-power [Watts]	High	795 ± 55	775 ± 69	-3%	-0.43	0.69	No
	Medium	n/a	n/a	n/a	n/a	n/a	n/a
	Low	454 ± 73	512 ± 60	13%	1.06	0.350	No
Thermal Efficiency [%]	High	41 ± 2.3	34 ± 1.5	-23%	-4.90	0.008	Yes
	Medium	n/a	n/a	n/a	n/a	n/a	n/a
	Low	33 ± 4.0	35 ± 5.5	6%	0.51	0.64	No
$CO:CO_2$ Ratio [%]	High	0.21 ± 0.16	0.12 ± 0.1	-72%	-0.53	0.62	No
	Medium	n/a	n/a	n/a	n/a	n/a	n/a
	Low	0.22 ± 0.22	0.26 ± 0.18	15%	0.23	0.83	No
Turn Down Ratio (Fire Power High: Fire Power Low)		1.75 ± 0.31	1.51 ± 0.22				

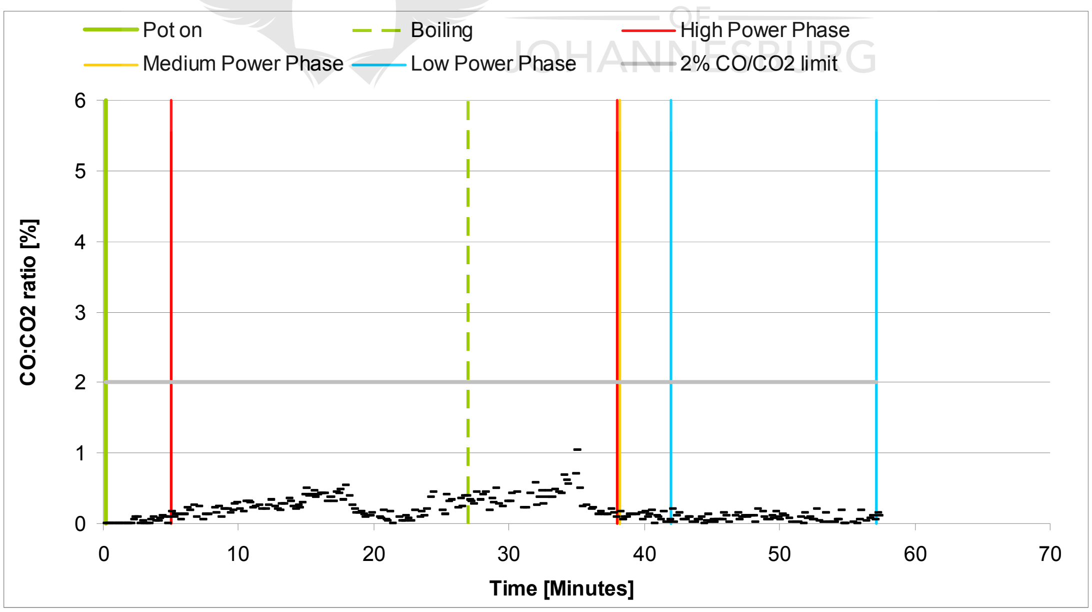


Figure 23: Combustion efficiency profile for the pressurised paraffin stove

4.3.4 *Task-based performance compared*

The *HTP* allows collection of task based data as in the WBT. Task based results from the three paraffin stoves evaluated are presented in Table 11. In all cases the fuel used and emissions produced to bring water to a boil are normalised to an equivalent 80˚C rise, so that specific fuel consumption and emission factors can be fairly compared between tests.

Results show that the specific time to boil water (time per litre) is quicker for the baseline paraffin than for the new type paraffin stove or the pressurised paraffin stove, for both pot sizes. This is due to increased average fire-power of the baseline stove at the *high* power setting compared to the other stoves. The pressurised paraffin gave the lowest fire-power at the *high* power setting, mainly due to continual blocking of the nozzles. It took twice the amount of time it took the baseline paraffin wick stove to boil water using both pot sizes. The baseline paraffin stove achieves a high fire-power with a low specific fuel consumption compared to the new type and pressurised paraffin stoves (Table 11). One would expect a stove with a high specific fuel consumption to give an increased fire-power at a given power setting, resulting in less time to complete a given task.

For all the stoves tested, the specific fuel consumption and the specific time to boil, increases with a reduction in the pot size (Table 11). This is potentially due to an increase in heat efficiency transfer when using a larger pot (greater surface area for heat absorption) than when using a small pot (less surface area and greater heat losses). It is evident from the results that in order to save fuel and time, a larger pot size is a better option compared to a small pot size.

Table 11: Task based system performance (bringing the water to boil at high) for the three paraffin stoves

Parameter	Baseline paraffin stove		New type paraffin stove		Pressurised paraffin stove	
	Large pot (Mean ± SD)	Small pot (Mean ± SD)	Large pot (Mean ± SD)	Small pot (Mean ± SD)	Large pot (Mean ± SD)	Small pot (Mean ± SD)
Time to boil [min]	37.2 ± 3.5	12.8 ± 1.4	53.0 ± 0.7	20.5 ± 1.7	87.2 ± 2.4	29.9 ± 1.8
Specific time to boil [min L^{-1}]	7.4 ± 0.7	8.5 ± 0.9	10.6 ± 0.1	13.7 ± 1.1	17.3 ± 0.6	19.9 ± 1.2
Specific fuel consumption [g fuel L^{-1}]	13.7 ± 0.3	16.7 ± 0.8	14.8 ± 0.1	19.0 ± 0.8	19.0 ± 1.5	23.1 ± 2.0
Specific CO emission [g CO L^{-1}]	0.78 ± 0.24	0.83 ± 0.17	0.76 ± 0.1	0.94 ± 0.2	0.04 ± 0.2	0.03 ± 0.02
Thermal efficiency at *high* setting [%]	60 ± 1.1	54 ± 1.5	53 ± 1.0	46 ± 1.0	41 ± 2.3	34 ± 1.5

All data is normalised to an 80ºC temperature rise

It has to be noted that there is a price to pay if one chooses the pressurised paraffin stove on the basis of low emissions and good combustion efficiency. Clearly the stove fails to perform basic function of continuous heating due to the continued blocking of nozzles. For boiling 5 L of water, the pressurised stove will take twice the time the baseline paraffin wick stove would take with the difference being sufficiently large for a user to complain. Thus there needs to be a compromise in selecting which stove to promote based on the task-based system performance of each stove.

4.3.5 Fire-power and efficiency compared

A fuel/stove combination can be characterised by a thermal efficiency versus fire-power graph. The purpose of the graph is to be able to distinguish between a good stove and a poor stove. Figure 24 shows the thermal efficiency versus fire-power graph of the three paraffin stoves, using a small pot.

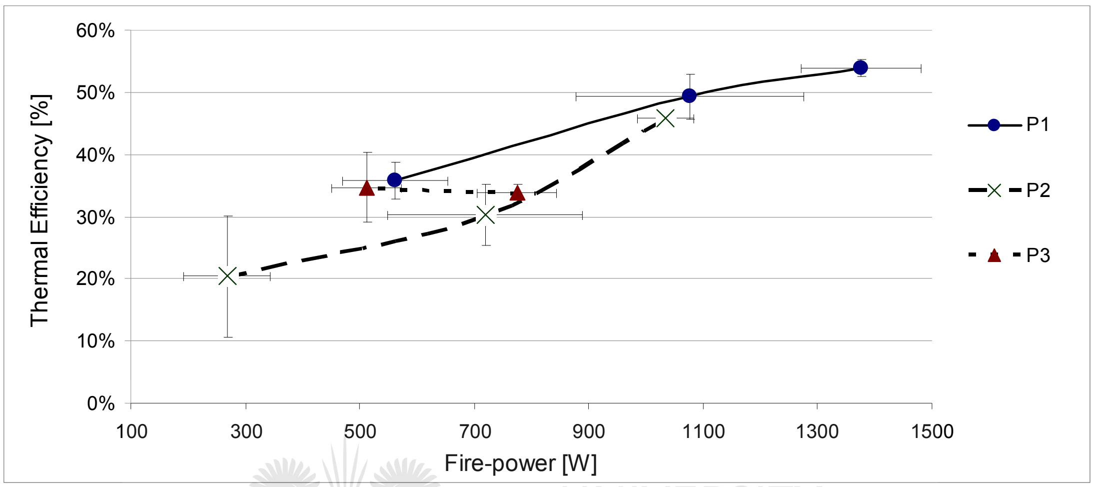


Figure 24: Thermal efficiency versus fire-power of: baseline paraffin wick stove (P1), new type paraffin wick stove (P2), and pressurised paraffin stove (P3), using a small pot

For a small pot case (Figure 24), the pressurised paraffin stove shows a profile where the thermal efficiency does not change with an increase in the fire-power. Although the stove shows a good thermal efficiency to fire-power relationship, it is far from ideal as the fire-power at high falls below 1 000 W and a thermal efficiency value of 35%. A fire-power of less than 1 000 W at *high* falls below the requirements of SANS 1906:2009 which stipulates that a stove has to produce a heat output of at least 1 000 W. The stove has to be further improved to meet the heat output requirements as stipulated by the SABS at *high* power and possibly for the thermal efficiency to rise above the 50% mark. Time is lost by the flame dying down and in unblocking the nozzles resulting in the pot losing more heat to the surroundings, thereby affecting the thermal efficiency and fire-power.

The paraffin wick stove showed some interesting results. The baseline paraffin wick stove (P1) showed a better performance curve compared to the new type paraffin wick stove (P3) (Figure 24). This is an unexpected result as the new type paraffin wick stove was designed as an improvement to the baseline paraffin wick stove both in terms of efficiency and safety. The baseline paraffin wick stove (P1) gave a fire-power output of 1 400 W on *high* with a thermal efficiency value of

55% and 560 W on *low* with a thermal efficiency value of 36%. The new type paraffin wick stove gave a fire-power output of 1 100 W with a thermal efficiency of 46% on *high* and 300 W on *low* with a thermal efficiency of 20%. As a result fire-power is reduced by a factor of 21% and a thermal efficiency by 10% on *high* power compared to the baseline.

For the large pot case (Figure 25), the baseline paraffin wick stove and the new type paraffin stove gave similar results to the small pot case (Figure 24). The pressurised paraffin stove shows an efficiency range of 30–44%. Thermal efficiency increases with fire-power as expected, because of reduced nozzle blocking during the large pot tests.

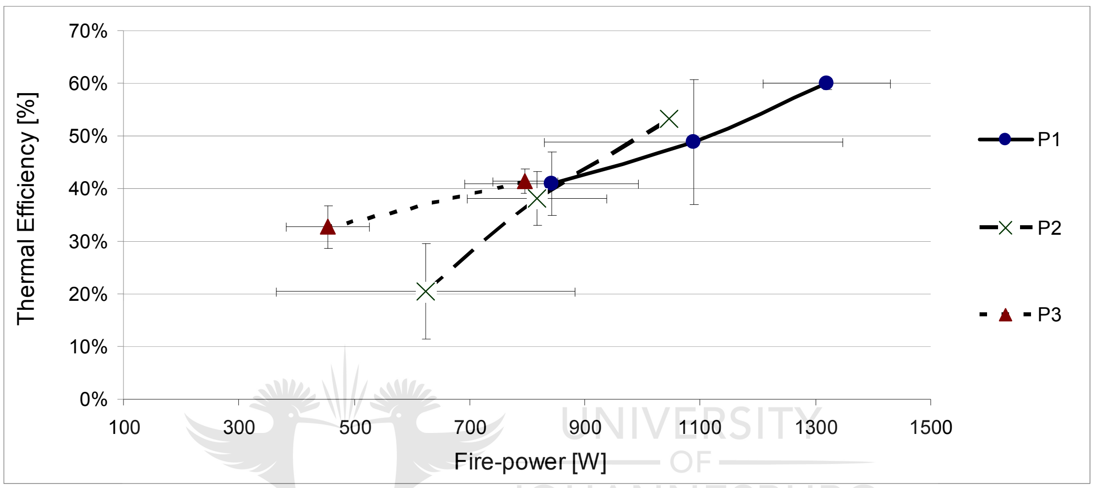


Figure 25: Thermal efficiency versus fire-power of: baseline paraffin wick stove (P1), new type paraffin wick stove (P2), and pressurised paraffin stove (P3), using a large pot

In ranking the stoves according to thermal efficiency against fire-power curves, it can be shown that the baseline paraffin wick stove is the best performer followed by the pressurised paraffin stove and the new type paraffin wick stove. In terms of safety, the pressurised paraffin stove is ranked higher than the new type paraffin stove and much higher than the baseline paraffin stove. These safety related evaluations are not reported in this study and are mentioned here to highlight the need for optimisation of domestic cooking devices both in terms of efficiency and safety.

4.4 Combustion Efficiencies of Coal Burning Stoves

4.4.1 Imbaula stove

Coal, due to its ready availability and relatively low cost, is the most common domestic fuel burned in the townships of the South African Highveld, either in formal stoves or informal *imbaula* (brazier) stoves. Two methods of ignition of the *imbaula* stove are compared in this study: the *bottom-lit up-draft* (BLUD) and the *top-lit up-draft* (TLUD) methods. The *bottom-lit up-draft* is the conventional/traditional way of lighting a coal fire, with the order of laying the fire proceeding as follows: paper, wood, ignition, after which coal is added at an appropriate time after the wood fire is established. The $CO:CO_2$ emissions profile from the conventional method of lighting an *imbaula* is presented in Figure 26. In the *top-lit up-draft* (TLUD) ignition method, also known as the *Basa njengo Magogo* (*BnM*), the order of laying the fire is reversed – first coal, paper, and then wood, with a few lumps of coal added at an appropriate time after the fire has been lit. The $CO:CO_2$ emissions profile from the *Basa njengo Magogo* ignition method is shown in Figure 27. In each test ~5 kg of coal was used.

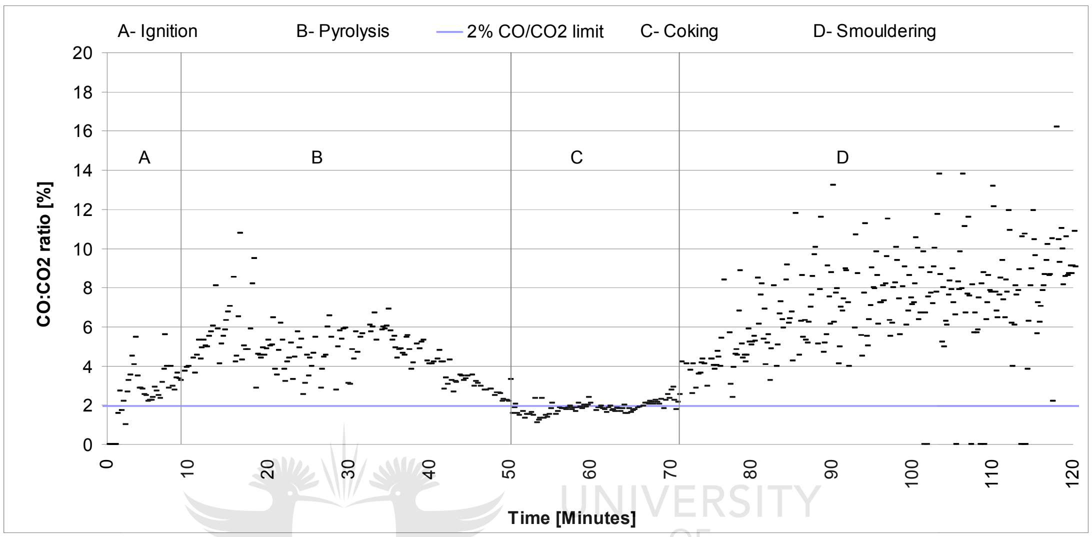


Figure 26: Combustion efficiency profile of a bottom-lit up-draft (BLUD) *imbaula* fire

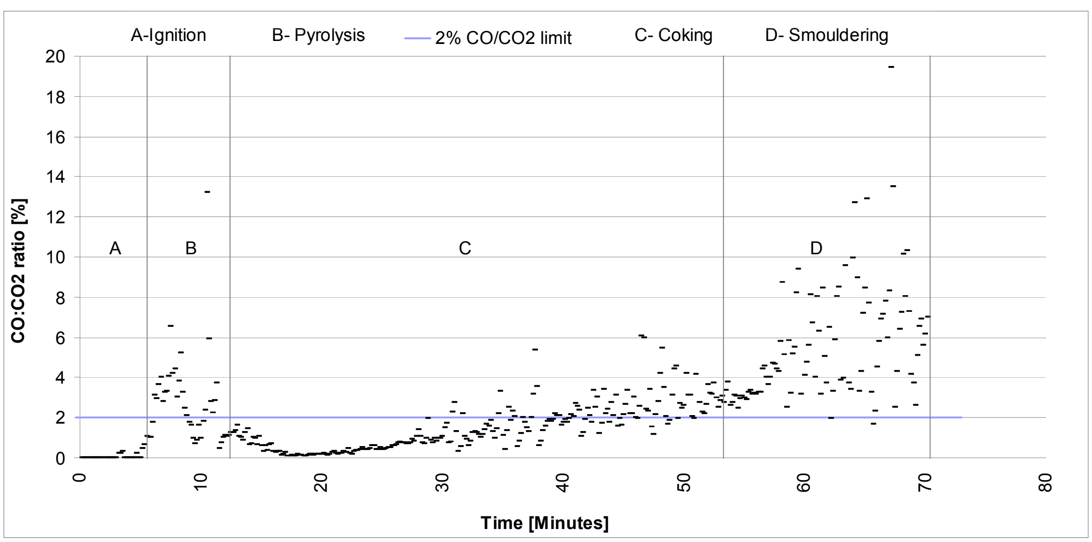


Figure 27: Combustion efficiency profile of a top-lit up-draft (TLUD) *imbaula* fire

The behaviour of the $CO:CO_2$ curves may be explained more readily by reference to the photographs of *imbaulas* ignited by the two methods (Figure 28 and Figure 29). For the BLUD, ignition at the bottom creates an upward migrating pyrolytic zone that is starved of oxygen;

generating a pyrolytic gas (CO, H_2O, volatile and semi-volatile compounds) and char. Zone A is the initial hot zone where the coal undergoes thermal decomposition. The coal swells resulting in the breaking of weaker bridges in its macro-structure, which produces tars and semi-volatile organic compounds (SVOCs) in a process known as devolatilisation. The removal of these volatiles increases the pore volume in the coal structure. The tars and semi-volatile organic compounds become pre-mixed with air around the surface of the coal macromolecules. Homogenous gas phase combustion of this pre-mixed fuel/air mixture occurs. The combusting gas mixture rises, using up available oxygen, and passes through the cooler coal above (Zone B). Coal in zone B may undergo some pyrolysis, but initially there is not enough oxygen or heat to sustain combustion. The semi-volatiles subsequently condensed into droplets as the cooling gas mixture passes through zone C into the atmosphere, resulting in the formation of a dense plume of white smoke (Figure 28). This poor combustion efficiency is indicated by the $CO:CO_2$ ratio in the range 4-6% during the pyrolysis phase (Phase B in Figure 26). The stove at this stage does not produce sufficient heat for cooking and has to be kept outdoors because of the excessive smoke. It would take up to 50 minutes for the combustion efficiency to improve ($CO:CO_2<2\%$) to the stage when the device could be taken indoors safely for cooking or space heating (Figure 26, phase C).

The temperature in the homogenous combustion layer is increased rapidly as the volatile matter is combusted, until there is insufficient volatile matter evolving from the coal macromolecules to sustain this combustion. The remaining and subsequently evolved volatile matter then experiences slower oxidation with a lower heat release rate. This marks the onset of the *coking* phase, which results in an excellent combustion efficiency (Figure 26, phase D). During this coking phase heterogeneous gas/solid combustion takes place, with the rate limited by diffusion of oxygen to the char surface. The product of the surface reaction is CO-rich, which undergoes further combustion in the gas phase to CO_2. In the final stage of the fire, referred to as the smouldering phase, the available heat and fragmentation of the residual char are insufficient to sustain complete CO combustion, and the CO emissions rise (Figure 26, phase D).

For the TLUD (e.g. *Basa njengo Magogo* ignition method), Zone B (Figure 29) is the hot zone where wood and a few lumps of coal are thermally decomposed. The decomposition results in the formation of volatile matter as discussed above. The ignition of a batch of fuel from the top creates a *downward* migrating pyrolytic zone that is starved of oxygen. Zone A is a colder zone filled with the bulk of the coal, which produces volatile matter and tars upon heating. This volatile matter rises through the hot flame zone (zone B) with a sufficient supply of oxygen to allow for complete homogeneous gas-phase combustion. This results in a significant reduction in visible smoke and particulates (Zone C). The flame that can be seen jumping out of the stove (Zone C) is as a result of an increase in the homogeneous gas phase combustion rate. The good combustion efficiency is indicated by the $CO:CO_2$ in the range 1-2% (Figure 27). The stove produces sufficient heat for cooking and is safe to take indoors, from a carbon monoxide point of view, ~12 minutes after ignition (Figure 27, phase C). After ~55 minutes from ignition, the final stage of char combustion is similar to the situation for the BLUD ignition method, with an increase of CO emissions. The initial lighting method has no influence on this last smouldering phase of combustion.

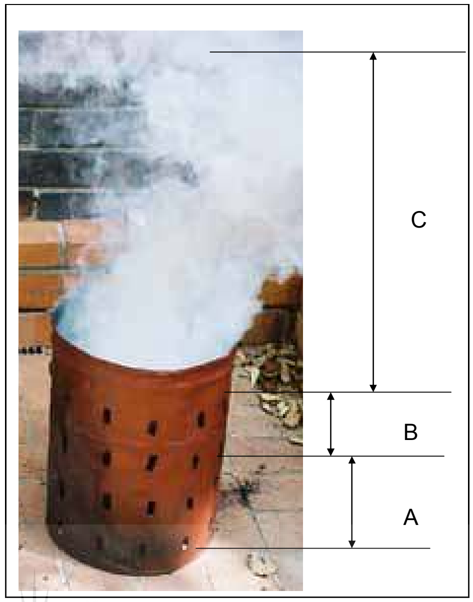


Figure 28: Initial combustion phases for the BLUD method

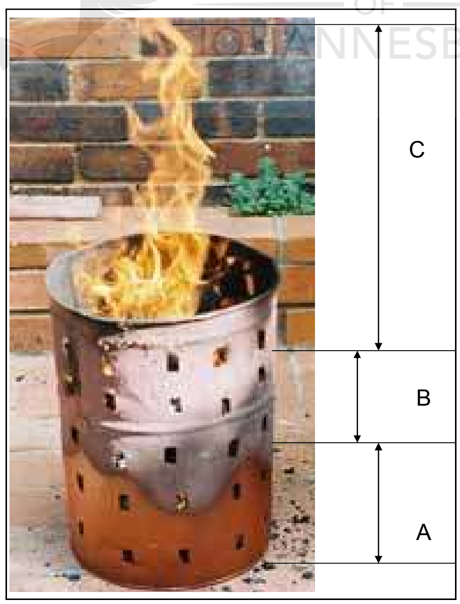


Figure 29: Initial combustion phases for the *Basa njengo Magogo* - TLUD

Comparing the two profiles, it can be seen that the BLUD ignition method shows a higher average $CO:CO_2$ ratio during the test compared to the *Basa njengo Magogo* ignition method. The average $CO:CO_2$ for the BLUD was found to be 5% and that for the *Basa njengo Magogo* method was found to be 2% with the $CO:CO_2$ ratio remaining fairly stable until the fire begins to die down.

The *Basa njengo Magogo* method reached a stage where the stove could be taken indoors or used for cooking after ~12 minutes (Figure 27, Point C), approximately 30 to 40 minutes (Figure 26, Point C) sooner than for the conventional BLUD method.

The *Basa njengo Magogo* method proved to be a better method of lighting a coal fire in an *imbaula* both in terms of reduced smoke generation (an indication of good combustion), and fuel savings. This result is similar to that of Anderson (2011), le Roux *et al*. (2009), and Bhattacharya *et al*. (2002) who found that the TLUD method had a better emissions performance compared to the BLUD method.

4.4.2 SeTAR bottom-lit down-draft (BLDD) coal stove

The SeTAR *bottom-lit down-draft* (BLDD) coal stove (see Section 3.1.7) was assessed for combustion efficiency.[19] A maximum of 1 kg of coal was used in this test as the hopper could not take more than 1.3 kg of coal. The stove burned 1 kg of coal from ignition to smouldering in ~240 minutes (Figure 30, phase A to D), indicating that it has a lower fuel burn-rate compared to the *imbaula* stoves. The $CO:CO_2$ ratio for a combustion test of this device is shown in Figure 30. The BLDD stove showed excellent combustion of coal from ignition (Figure 30, phase A) to smouldering (Figure 30, phase D). The stove gave a $CO:CO_2$ ratio of less than 0.2% for ~160 minutes. After ~160 minutes the $CO:CO_2$ ratio slightly increases to approximately 0.7% and stabilises for a further 50 minutes. The useful combustion cycle was thus ~230 minutes. Thereafter, as the fire is dying down, the $CO:CO_2$ ratio increased to 12% (Figure 30, phase D).

The low $CO:CO_2$ is as a result of a good air to fuel mix through the use of optimised primary and secondary air during the *coking* process resulting in more complete combustion. A bed of red hot coke lies on the grate, through which all volatiles and combustible gases must pass to get to a combustion chamber, which lies below the grate. A controlled quantity of pre-heated secondary air is injected into the combustion chamber to produce a turbulent, high temperature flame with low excess air. The downward draft through the coal bed is sustained through the thermal draft induced by an appropriately designed chimney. The high (12% $CO:CO_2$ ratio) in the smouldering phase (Figure 30, phase D), indicates a need for further design considerations to lower the $CO:CO_2$ ratio, as this high emission rate has the potential to contribute to air pollution.

[19] The SeTAR bottom-lit down-draft stove was designed and built by Crispin Pemberton-Pigott.

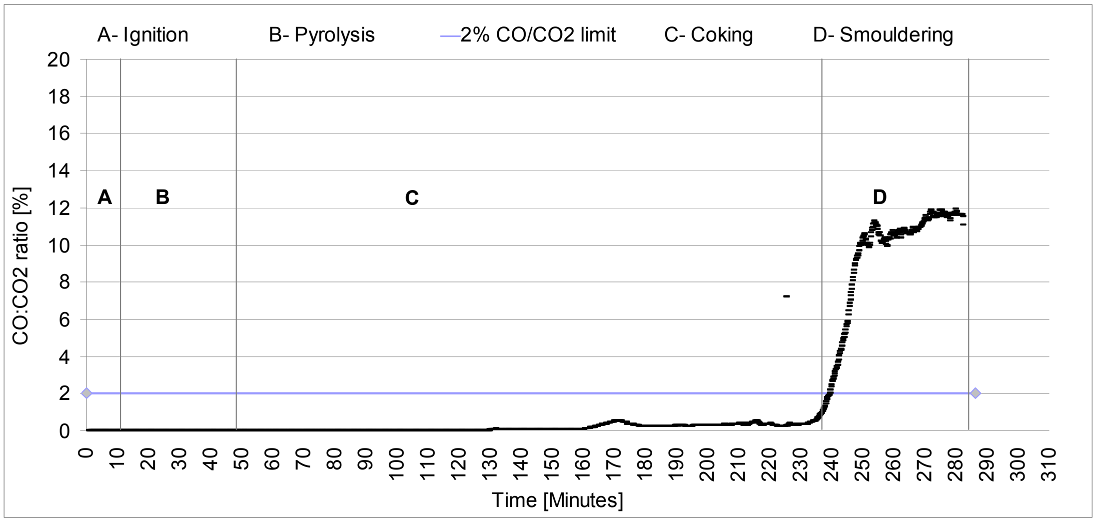


Figure 30: Combustion efficiency profile of a coal BLDD stove

(Credit: SEET Laboratory, Ulaanbaatar, Mongolia)

4.5 Thermal Performance of Charcoal Burning Stoves

The performance of a new type of a commercially available ceramic charcoal stove (described in Section 3.1.6) was compared against a baseline, in the form of a traditional metal charcoal stove (described in Section 3.1.5) from Mozambique. To better reflect the real world use of these devices, the *HTP* was adapted in two key areas. Firstly, as performance can be affected by the quantity of charcoal that is batch loaded into the stove, the protocol requires that tests are conducted with two distinct charcoal loads that reflect either the manufacturer's recommendations (600 g, which partially fills the hopper), or common use (observed practice is to fill the hopper to the upper lip, ~900 g). Secondly, as there is no mechanism to control the power output of the stove, a single charge of fuel is used and the fuel is left to burn through a full cycle (from ignition to 90% fuel consumption) and the thermal performance assessed over the entire burn cycle. A hot start test (such as required by the WBT) is not applicable to these stove types as they do not have high heat capacities and cool rapidly during the time taken to unload the ash and re-charge the stove.

Early tests conducted with the same 600 g mass of fuel in each stove (Figure 31) showed that the new type ceramic stove had an improved thermal efficiency (32% to 41%) relative to the baseline device (28%). However, in many households the traditional stove was often used with a larger fuel load of 900 g. In the laboratory, a test with this representative fuel load in the baseline device resulted in a thermal efficiency that was not significantly different ($p>0.05$) between the new ceramic and the baseline metal stove. This may be due to the reduction in the gap between the base of the pot and the fuel, allowing for efficient radiation. However, batch loading the stove above its capacity often results in the quenching of the fire which leads to poor combustion and reduced thermal efficiency.

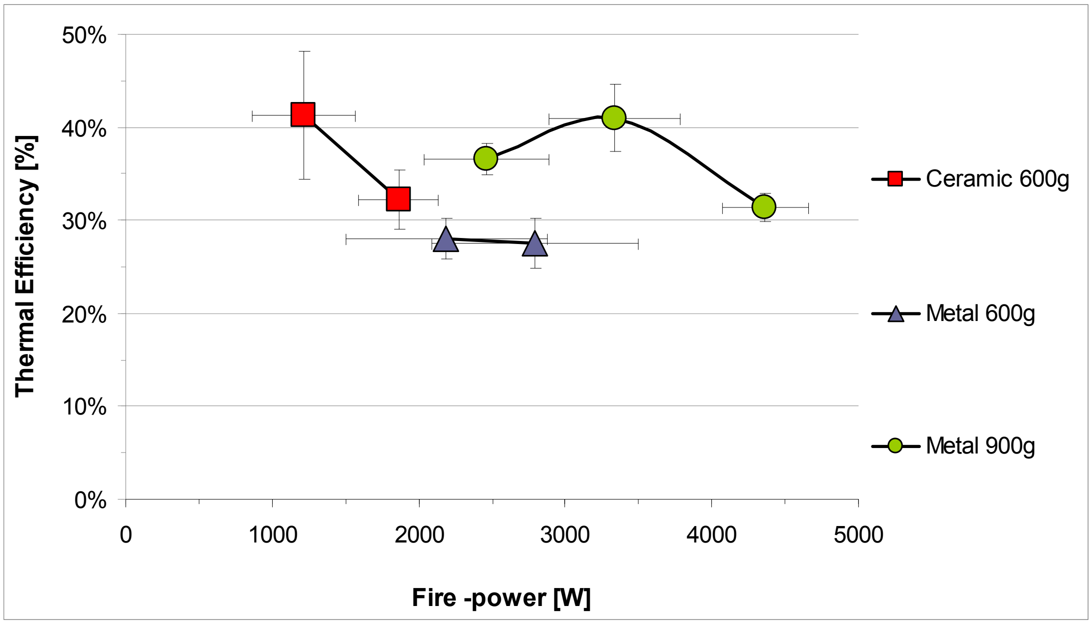


Figure 31: The relationship between power and thermal efficiency with a traditional Mozambican metal-construction charcoal stove, and the new type ceramic Mozambican charcoal stoves

4.6 Comparison between the *Heterogeneous stove Testing Protocols* and the Water Boiling Test Version 3.0

This section addresses the following objective:

- Perform a conceptual comparative evaluation of new protocols and the Water Boiling Test Version 3.0.

The comparative analysis will be based on a set of criteria highlighted in Section 2.1. In addition, parameters from both test methods will be compared, from definition to purposes of deriving each parameter. There is need to identify where the parameters in the two tests are essentially similar (reporting the same result) or where they are qualitatively different (in which case there is no good purpose served in putting the values side to side even though similar terminology might have been used to describe that portion of the test). These comparisons will be used in the assessment of the robustness of each test method in performance evaluations of diverse fuel/stove combinations.

- *Does the protocol measure greenhouse gas emissions over an entire cycle that is representative of real-world uses of stoves?*

From the illustrative examples given in this chapter, it can be seen that the *HTP* measures greenhouse gas emissions over an entire burn cycle that is representative of the real world uses of fuel/stove combinations. Emission factors are calculated for each phase of the fire across a full range of power settings. Like the WBT, it is possible to average the emission factors of gases for the entire burn cycle using the *HTP* to obtain a single efficiency (thermal or emissions) number.

The peculiarity of the protocols is evident in the fact that it is possible to identify stove design errors at different power settings by looking at the emission factors and the combustion efficiencies at these power settings. Such a profile is missed when one uses the WBT, which does not test the stove across its full range of power settings and at a simmer setting. Using continuous measurements of emission rates, it is possible to substantiate combustion efficiencies during discrete burn events, typical of stoves used in real-world use. Since efficiency varies significantly with fire-power during the different phases of the burn cycle, a single efficiency number may not be a good performance indicator (Johnson *et al.,* 2010; Prasad *et al.,* 1985). The *HTP* addresses this shortfall by considering efficiency numbers at each power setting. Thus, compared to the WBT, the *HTP* gives more comprehensive and representative estimates of emissions and thermal efficiency numbers.

- *Does the protocol allow testing of fuels typical to the target area?*

Considering the fuels used in the tests, the *HTP* is flexible and not prescriptive on the fuel type, fuel load, and fuel size. The WBT, for example, highlights that "…*thoroughly air dried sticks of 3-4 cm in diameter with a 10-20% moisture content…*" (Bailis *et al.,* 2007b:10) should be used. EPA method 28 stipulates the use of red or white oak with a moisture content of 19 to 25% on a dry basis. This is done in an effort to standardise the test and this often leads to conditions that are not typical to real world uses of fuels and stoves. The *HTP* allows for the use of a variety of fuels (type, size and load) typical to the target area (for example as discussed in 4.5). Variations in the fuels, for example in terms of the moisture content and calorific values, are accounted for in the stove performance calculations. Instead of using available documented calorific values of a variety of fuels, it is recommended that when using the *HTP* each batch of fuel is analysed for its moisture (if relevant) and calorific value prior to testing.

- *Does the protocol allow for the identification of stove design weaknesses and advantages?*

The *HTP* allows for the identification of stove design weaknesses and advantages unlike the WBT. The WBT requires testing of fuel stove combinations at a *high* power setting and a simmer setting. However, more power is needed to maintain the water below 3°C of boiling when not using a pot lid. On the other hand, the *HTP* allows for the testing of stoves across a full range of power settings (*high*, *medium*, *low*). A stove may inherently perform poorly at the *medium* power setting as shown in the combustion efficiency profile of the new type paraffin wick stove in Section 4.3.2. This profile will be missed if the testing regimen ignores the *medium* power setting. In South Africa the *medium* power setting on these devices is typically used for simmering meat, legumes and rice. Thus high gas emission factors exhibited during this power setting has the potential to contribute significantly to inventories of greenhouse gas emissions and increased levels of indoor air pollution.

Since the WBT uses an indeterminate simmer setting (somewhat higher than the lowest power setting of the stove) during the testing procedure design weaknesses or strengths at the lowest power setting may not be identified. In South Africa the lowest power setting is used during night for space heating, and for keeping food warm. It is an important design principle to critically evaluate emissions and thermal performance of fuel/stove combinations across a full range of power settings. This type of evaluation is done to target for improvement those parts that produce the most CO_2 equivalent and products of incomplete combustion.

- *Does the protocol allow for the expression of results in a normalised manner for direct comparisons between different fuel/stove combinations?*

The *HTP* allows for the expression of results in a normalised manner for direct comparison between different fuel/stove combinations. Unlike WBT, emission factors as used in the *HTP* are normalised to a chosen reference value of zero percent excess air. The normalisation of these results to a reference value allows for direct comparisons between different fuel/stove combinations. Results from the Water Boiling Tests are not normalised to a reference value thus making it impossible to compare between different fuel/stove combinations.

- *Is the protocol certified by certifying bodies?*

Existing protocols in use are not certified by certification bodies resulting in irregularities and variations in the testing regimen and stove performance analytical processes. From the starting point that the Water Boiling Tests prescribes a fixed point of performance with a single pot size, we started to devise a test protocol from first principles that, as it matures, will be presented to standards certification bodies (e.g. TÜV Rheinland and ASTM) for validation and certification. The detailed standard operating procedures will be posted on the open web at an appropriate stage. This fulfils the objectives of CDM projects in terms of the need for validation and certification of projects and processes by an independent body.

4.6.1 Comparison of parameters between the test methods

There are subtle differences exhibited in the intent of the methods. The *HTP* intends to rate the performance of the fuel/stove combination across a range of conditions. The Water Boiling Test (WBT), on the other hand, intends to measure the fuel consumed when performing a particular task. As a result, various procedural differences exist between the WBT and the *HTP*. There is a need to assess the differences vis-à-vis the final reporting numbers obtainable from each method.

Different opinions exist regarding the use of the lid during the test. The WBT suggests that tests be carried out without the use of a pot lid. "*The main purpose of the WBT is to quantify the way that heat is transferred from the stove to the cooking pot. While a lid helps to retain heat in the pot, and should therefore be used for any actual cooking task, it does not affect the transfer of heat from the* *stove to the pot. Hence, a lid is not needed for the WBT even if lids are commonly used among communities for which the improved stove is intended*." (Bailis *et al*., 2007b:13). The *HTP* recommends the use of pot lids during the tests. This is based on the premise that pot lids are used in the preparation of meals and show good cooking practise and that there is a need to evaluate the stove-fuel-pot-lid nexus as commonly used in homes. Bailis *et al*. (2007b:13) agree that "…*the indicators derived from the low power test are more sensitive to the amount of water evaporated*" and this has the potential to increase error in the reporting of parameters at this power setting. Again, Baldwin (1987) contends that "…*by not using a lid, evaporation rates are higher and the stove must be run at a somewhat higher power to maintain the temperature than is the case with a lid*" (Baldwin, 1987:255).

Regarding the size of the pot used during the test, the WBT recommends that the tester choose whether they will use a large pot (5 L of water) or a small pot (2.5 L of water). There is no mention of using both pot sizes in the performance evaluation of fuel/stove combinations. The *HTP* recommends the use of 6 L and 3 L Hart™ type pots and water quantities (5 L and 2 L of water) commonly used for cooking in South Africa and the region, for the performance evaluation of stoves. The test results are reported for both and the small pot cases.

The WBT recommends the use of a *high* power setting for the boiling test and a *low* power setting for the simmering task. The stove would require a somewhat higher power to keep the water simmering. Thus, what is normally referred to as *low* power is a setting close to the *medium* power setting of the stove. Only thermal parameters are evaluated using the WBT test procedure. In contrast, the *HTP* evaluates both thermal and *emissions* parameters. The *HTP* evaluation tests the stove across a range of power settings (*High*, *Medium*, *Low*) for stoves that can be controlled to operate at their discrete power settings. However, the protocol and the template for calculations are flexible to allow for reporting on stoves that do not have power controls e.g. charcoal stoves.

The WBT procedure recommends carrying out a hot start test. "*A hot-start test is incorporated in the high power phase in order to account for the different performance of stoves that are kept hot throughout the day. This is important for massive stoves, whose performance may vary significantly between cold and hot starting conditions*." (Bailis *et al*., 2007b:14). Because the hot-start phase is incorporated in the *high* power phase, the final reported figures are an average between the *high* power test and the hot-start. This can lead to different results to those obtained from the *HTP* which does not recommend carrying out a hot-start test. The fact that the hot-start applies to some stoves and not to others could lead to inconsistencies in reporting the performance of stoves. As a result, test results obtained using the two procedures may not be directly comparable.

Computational differences are evident in the two test methods. Comparison of qualitative results is not possible because the parameters measured are essentially different. The following parameters will be compared between the two test methods: thermal efficiency; specific fuel consumption; time to boil; burn rate; turn-down ratio; and fire-power.

With regards to thermal efficiency calculations, the WBT calculates thermal efficiency for the simmer phase. Instead of a simmer, the *HTP* employs an objective test referred to, by the cookstove group, as the *constant temperature rise* method (www.cookstove.net). A fresh pot of water is placed on the stove at the *low* power setting and the temperature of the water is allowed a 40 ºC rise from ambient to ~70 ºC. This method has the potential to give a correct assessment of the thermal parameters of the stove, minimising evaporative losses and errors inherent in trying to maintain water simmering at 3-6ºC below boiling. A simmer is difficult to maintain and requires the user to fiddle with the controls to adjust the fire-power of the stove, causing the water temperature to fluctuate. This leads to questions about the usefulness of this metric. We conclude that the *HTP* tests at *medium and low* power provide a more reproducible and precise test of stove performance at reduced power settings than the *simmering* test prescribed as part of the WBT.

The *HTP* recommends that all tests be run with a pot lid on. As suggested above, a pot lid minimises evaporative losses which accounts for error in the determination of thermal efficiency. The usefulness of this is evident in the calculation of emission factors (EF) per useful energy (g MJ^{-1} of useful energy) where there is need for a specific value in the efficiency number. Emission factors are not the same for different power settings and it is therefore important not to have unaccounted for energy losses (steam) in efficiency calculations. The WBT simmer is subject to a systematic error of accumulation and is dependent on operator judgment in continuously adjusting the fire-power of the stove. It also relies on measuring the vapour loss from the water between the beginning and end of the simmer period, inherently resulting in a small number, thus a potentially large relative error in this difference.

The purpose of the *low* power test with the *HTP* is to evaluate emissions and thermal performance of the stove under plausible conditions of use. It is necessary to cover a full range of the stove power settings. This is an additional functional test not mentioned in the WBT.

The definition of the term *turn-down ratio* is used by both test methods. Although based on a similar concept, the definitions for calculating this parameter differ. The WBT calculates the turn-down ratio as the ratio of the stove *high* power output to its low simmer (normally a mid-range power) setting. The *low* power setting employed by the WBT is empirically determined by keeping water simmering for a defined length of time (45 minutes). Thus the fire-power during the simmering task is dependent on user judgement and is difficult to reproduce in a precise manner. The *HTP* defines the turn-down ratio as the ratio of the stove fire-power at the *high* power setting to its fire-power at a *low* power setting. For stoves that have a power control, this *low* power setting is indicated by a dial setting or a stop, and is thus generally (but not always) a reproducible setting As a result of these differences, the *turn-down ratios* obtained using these two procedures may not agree and should be not directly compared.

Other parameters are reported and calculated in the same way and can be compared for the two test protocols. These include: burn rate; specific fuel consumption; time to boil. With regards to specific fuel consumption, the WBT normalise the data to a 75ºC temperature rise. "*This corrects specific consumption to account for differences in initial water temperatures. This facilitates comparison of stoves tested on different days or in different environmental conditions. The correction is a simple factor that 'normalizes' the temperature change observed in test conditions to a 'standard' temperature change of 75ºC (from 25ºC to 100ºC)*" (Bailis *et al*., 2007b:26). The *HTP* normalises the temperature change observed in test conditions to an 80ºC rise. Both methods need to address this issue by representing specific fuel consumption results in grammes of fuel consumed per degree per minute (g $ºC^{-1}$ min^{-1}).

Instead of attempting incremental improvements to the WBT that was developed for a specific purpose (for which purpose it was no doubt well suited), at a specific time, we have started from basic principles to devise a new test protocol adjusted to a new set of requirements. While some may find an interest in comparing the results of the two protocols, in general we prefer and recommend to focus on building a body of testing outcomes (thermal and emission performance), based on the new *HTP* protocol, that more readily allow inter-comparison across a broader range of stoves and fuel types. Differences in definition of the parameters and range of parameters determined by each test, as discussed in this chapter, make such direct comparisons of limited value.

CHAPTER FIVE

This chapter presents a summary of the main findings of the study. The chapter ends with a conclusion with reference to the hypothesis of the study and recommendations for further study.

5. Summary and Conclusion

5.1 Summary

The major objectives of this study were: (i) to critically evaluate the Water Boiling Test version 3.0 and other existing stove testing protocols; (ii) to develop a set of criteria needed for a stove testing protocol for CDM certification; (iii) to develop a set of testing protocols for the quantification of combustion gas emissions and thermal performance from domestic fuels and cooking devices; (iv) to document a set of standard operating procedures for all phases of the newly developed test procedure; (v) to carry out a comparative evaluation of paraffin fuelled stove *gas emissions* using the developed protocols; (vi) to measure and compare the *thermal performance* of existing and improved paraffin and charcoal burning stoves; (vii) to characterise *combustion efficiencies* from Top-Lit Up-Draft (TLUD), Bottom-Lit Up-Draft (BLUD) and Bottom-Lit Down-Draft (BLDD) coal burning stoves; and (viii) to conceptually evaluate the developed protocols in comparison with the Water Boiling Test version 3.0.

5.1.1 Evaluation of stove testing protocols

A critical evaluation of the WBT Version 3.0 has been presented in Chapter 2. This work has demonstrated that there is a wide range of emissions associated with the normal variations of pots and power settings of stoves as seen in real world conditions. In addition, the extrapolation of emissions based on tests that consider only a maximum power setting, a low power (simmer) setting, and boiling water in a single pot (without a lid) may not adequately represent the real-world emissions that it is intended to model. The imposition of standardised fuels imposes conditions that may be unrepresentative of real-world uses or likely combinations of fuels, stoves, and pots and incompatible with the practical operation of stoves. Tasks, being combinations of efficiencies, cannot be deconstructed to reveal the underlying efficiency numbers. Thus there was found need to develop an alternative testing procedure for thermal performance and gas emissions from domestic flame stoves, to extend the traditional *Water Boiling Test* by incorporating a range of power settings and pot sizes, and allowing also for the use of fuel types and quantities applicable to the stove design.

5.1.2 Development of a set of criteria for CDM projects

A set of criteria were developed for stove testing protocols useful for CDM projects and are discussed in detail in section 2.1. These criteria were developed to address issues of representation of the stove testing regimen to real world uses of fuel/stove combinations, in terms of emissions evaluations; use of fuels typical to a target area; identification of stove design defects; and the validation and certification of the protocols. The *Heterogeneous stove Testing Protocol (HTP)* is reported to meet all set criteria save for the one on certification as shown in Section 4.6. As the *HTP* matures, the protocols will be sent for validation and certification to bodies such as ASTM and TÜV Rheinland. Compared with existing Water Boiling Tests, the *HTP* is more adapted for CDM certification, even though the focus of Gold Standard carbon credit claims is on reduction of fuel consumption rather than on specific emissions produced by the devices.

5.1.3 Development and documentation of a set of protocols and standard operating procedures

The *HTP* was developed and documented as a complete set of standard operating procedures (SOPs), given in full in the Appendices, with separate SOPs presented for the determination of (i) thermal and emissions performance of fuel/stove combinations; and (ii) operation of the Testo® flue gas analyser. The *HTP* SOPs were designed to meet a number of basic requirements and criteria based on a template adopted from the Desert Research Institute (DRI), Reno, Nevada. The template was not modified during the documentation of our *HTP* protocols and care was given in filling all the relevant sections. Where information was not available due to the nature of the procedure, this was indicated as such. The language was adopted and adhered to throughout the development and documentation process.

5.1.4 Comparative evaluation of paraffin fuelled stove gas emissions

Gaseous emissions were investigated for three paraffin fuelled stoves using the *HTP*. For all the stoves tested, it was found that there is no significant difference ($P>0.05$) in gaseous emissions produced at the same power setting whilst varying pot sizes. For the pressurised paraffin stove (using both pot sizes) there was found to be no statistically significant difference in the CO emitted across a full range of power settings. This is attributed to the design mechanism of the stove, which results in combustion being unaffected by air dynamics around the pot. Thus pot size is not an important factor with regards to gaseous emissions from the three paraffin stoves tested.

As *high* power operation is usually the worst case scenario for emissions, the SABS testing protocol (SANS 1906:2009) requires that the stove be run at this maximum setting, predicting a consistent $CO:CO_2$ (v/v) result. For all the stoves tested, there was no statistically significant difference ($p>0.05$) in the calculated $CO:CO_2$ ratio as pot sizes are varied. This shows that pot size may not have an effect on the combustion efficiency of the paraffin stoves tested. The pressurised stove gave an acceptable (in terms of the SANS 1906:2009 standard, limit of 2%) $CO:CO_2$ ratio below 1% over a full range of power settings.

5.1.5 Thermal and fire-power performance of paraffin fuelled stoves

The method of placing a fresh pot of cold water on the stove for the tests at each power setting has the potential to minimise errors (in thermal parameters), resulting from excessive evaporation losses (Bussmann, 1988). For all the paraffin stoves tested, there was found to be no statistically significant difference ($p>0.05$) in thermal efficiency, when varying pot sizes at the *medium* and *low* power settings. A statistically significant difference was noted for the *high* power scenario. This shows that pot size may affect the thermal efficiency of the tested stoves at the *high* power setting.

When comparing the two paraffin wick stoves, it was shown that the baseline paraffin wick stove had an average fire-power of 1 400 W on *high* and 560 W on *low*. The new type paraffin wick stove showed an average fire-power of 1 100 W on *high* and 300 W on *low,* a reduction factor of 21% on *high* compared to the baseline. From the illustrative examples given in this thesis, the new type paraffin wick stove showed no improvement in the system performance with reference to the baseline paraffin wick stove. However, the new type paraffin wick stove has additional features for fire safety precaution, the main aim of improvements required in terms of SANS 1906:2009.

The performance of the pressurised paraffin stove was substantially reduced by the progressive blocking of the nozzle with carbon particles. The drop off in performance resulted in the stove giving a maximum fire-power of 800 - 850 W at a *high* power setting, and a thermal efficiency of 35-41%. This fire-power falls short of the requisites of the SABS standards for paraffin fuelled cookstoves. This highlights the need for design changes to the stove to meet the thermal and fire-power requirements. Fire-power of pressurised stoves can be increased by increasing the diameter of the nozzles. Despite these shortfalls, the pressurised paraffin stove gave a better overall performance than the paraffin wick stoves. In future tests, a pressure gauge can be used to control the device across a range of power settings. This would also allow for the introduction of a reproducible *medium* power setting in the pressurised paraffin stoves.

The variability in the fire-power in the reported results is unreasonably high, maybe due to the difficulty of obtaining reproducible settings on the continuous variable movement of the wick. Relying on estimate of power settings from a poor mechanical control leads to results with high variability. In future tests this could be overcome by using a Vernier calliper to adjust the height of the wick to preset values for each power setting; this might allow for a more precise estimation of thermal and emission parameters across the range of power settings.

5.1.6 *Combustion efficiencies from TLUD, BLUD and BLDD coal stoves*

Two methods of stove ignition — Bottom-lit Up-draft (BLUD) and the *Basa njengo Magogo* (*BnM*) also referred to as the Top-lit Up-draft (TLUD) — were investigated in the *imbaula* type stove using the *Heterogeneous stove Testing Protocol*. The *Basa njengo Magogo* method proved to be a better method of lighting a coal fire and appeared to burn the coal with much less smoke compared to the BLUD method, particularly during the start up phase. The BLUD method gave an average $CO:CO_2$ ratio of 5% over the entire burn cycle. This is at variance with the *BnM* method which gave an average $CO:CO_2$ ratio of 2.1% across the same conditions.[20] The TLUD *BnM* method reached a stage where the stove could be taken indoors or used for cooking after 11 minutes, approximately 30 to 40 minutes sooner than for the conventional BLUD method.

The bottom-lit down-draft (BLDD) method was investigated, in a prototype stove, following the *HTP* and showed excellent combustion of coal from ignition to smouldering. The BLDD stove gave an average $CO:CO_2$ ratio of 0.1% over a cycle which lasted ~160 minutes. However, the $CO:CO_2$ ratio increased significantly to 12% as the fire died down, pointing to the need for design considerations at this phase of combustion. Based on the combustion efficiency figures (as indicated by the $CO:CO_2$ ratio), the BLDD is ranked better to the *Basa njengo Magogo* method and the BLUD method.

5.1.7 *Thermal performance of charcoal stoves*

Two discrete charcoal masses which were used during the evaluation of a ceramic stove manufactured and marketed in Maputo. The two fuel loads reflect common use (filling the hopper to capacity) and manufacturer's recommendations (smaller load). A single charge of fuel loaded in the stove was left to burn through a full cycle (from ignition to 90% fuel consumption), with thermal parameters assessed over the entire burn cycle. Results showed that there was no significant difference in the thermal efficiency between the new ceramic two charcoal stove compared to the traditional Mozambican metal construction charcoal stove. This indicates that for the performance evaluation of batch loaded solid fuel stoves, there is a need to optimise them with probable fuel loads and sizes as commonly used or as recommended by the stove manufacturer.

5.1.8 *Comparison of the Heterogeneous stove Testing Protocols with the Water Boiling Test Version 3.0*

A conceptual comparison between the *HTP* and WBT was carried out based on a list of chosen criteria for CDM projects (see Section 2.1). From the comparison it was established that the *HTP*

[20] The particle testing apparatus was not available at the stage of the development of the laboratory and will form part of an extended *HTP*.

creates performance curves covering a range of use scenarios. These curves can then be used for design purposes, and in making informed decisions regarding the types of stoves to promote. Table 12 gives a summary of the conceptual comparison between the WBT version 3.0 and the *HTP* based on the criteria presented in Section 2.1, and the detailed evaluation Chapter 4.

Table 12: Summary of conceptual results from the WBT version 3.0 and the *HTP*

Criteria Used	WBT Version 3.0	*HTP*
Representative emissions over an entire burn cycle	- cannot measure emissions over a range of conditions. - emissions and thermal efficiency are an average of a burn cycle. - trade off between efficiency and emissions cannot be investigated.	- measures emissions over a range of conditions. - emissions and thermal efficiency are recorded continuously rather than averaged over the entire burn cycle. - trade off between efficiency and emissions investigated (determine polluting phase).
Identification of design weaknesses and strengths	- method does not use continuous assessment of emissions and thermal efficiency over burn cycle. - sums performance metrics over a range of conditions to give a single integrated number for each metric.	- method uses continuous assessment of emissions and thermal efficiency over an entire burn cycle. - performance metrics determined at different phases of the fire
Expression of results for comparison between different stoves	- emission factors are not normalised for excess oxygen. - difficult to compare between different stoves performing different tasks	- emission factors are normalised for excess oxygen. - possible to compare between different stoves performing different tasks
Allow testing of fuel typical to a target area	- does not allow for testing of fuel typical to a target area	allows for testing of fuels typical to a target area
Certification by independent bodies	- not certified by an independent stove testing certification body - objective is to get it adopted before certification	- not yet certified by an independent stove testing certification body - objective is to get it certified before adoption

Parameters from the two test methods were compared. For example, the *turn-down ratio* as defined differently by both test methods, and there is no need to compare the output. Similarly, this applies for qualitative tests. The hot-start phase of the WBT is a relevant parameter for large institutional stoves or for stoves with a high heat retention capacity. It is less useful for stoves with a low thermal mass, for example paraffin stoves (in which case hot refuelling could be potentially hazardous) or solid fuel stoves without a ceramic lining.

The intermediate power tests in the WBT are simulated by a simmering test and the *HTP* by a *medium* (mid-range) power setting test in which water is heated from ambient to ~70ºC. Our assertion is that the *HTP* calls for precise determination measuring well defined parameters (e.g. energy efficiency) which avoids *errors of accumulation* becoming significant in the energy efficient test and does not rely on operational judgment in continuously adjusting the fire-power of the device. The WBT relies on the steam loss from the water for the intermediate simmer test and this number is derived as a small difference between the mass of water at the beginning and end of the simmer period, thus the relative error in this difference is potentially large.

The *HTP* at a *low* power setting completes a set of measurements over the full range of the stove allowing for characterisation of the stove design and also representing possible real-world uses of the stove. For many solid fuel stoves there are either no convenient or practicable methods to adjust the power setting of the stove. Both test protocols need to be adjusted to take account of this.

5.2 Conclusion

Stoves are now of a global interest due to the introduction of the *Global Alliance for Clean Cookstoves* (www.cleancookstoves.org), and there is a necessity for stove testing methods to be described to a high professional standard so that the methods can be transported and evaluated within international programmes. This thesis aimed to develop a set of testing protocols for determining thermal efficiency and emissions performance of domestic fuels and cooking devices to satisfy the rigorous performance specifications expected for claims under the Clean Development Mechanism (CDM) and Gold Standard carbon trading markets. The *HTP* hypothesised that pot sizes could be an important parameter in the evaluation of fuel/stove combinations. Pot size was found not to be a significant variable or key parameter in the assessment of the three paraffin stoves tested indicating that a single pot size test was sufficient for these stoves. Fuel load was assessed for the Mozambican charcoal stoves and it was concluded that the amount of fuel batch loaded into the stove affect the thermal properties of the stove, highlighting the need to asses a stove using fuel size, and load as commonly used. Importantly, it was shown that fire-power affects to a degree, performance of the paraffin stoves tested and evaluating each stove across a range of power settings enabled the formation of performance curves. These are important in assessing thermal parameters and emissions over an entire burn cycle, and necessary for identifying design strengths and weaknesses of the stoves.

Through the establishment of a committee of the *Engineers in Technical and Humanitarian Opportunities of Service* (ETHOS) and consequent follow up ETHOS conferences, the WBT has been subject to regular reviews and refinements over a number of years. Among the scholars who have critiqued the WBT Version 3.0 in recent years is Taylor (2009). In his MSc thesis, Taylor (2009:15) contended that the WBT has limited application in predicting actual field performance as the measures of performance are done in a way that is applicable to a narrow range of use cases. He critiqued the use of a standardised fuel and test pot; fire-power; turn-down ratio; simmer; and energy accounting. However, his critique was based on a presentation of conceptual arguments, not on experimental data collected from performance evaluations of a variety of fuel/stove combinations. He recommends that future protocols should be able to capture and include issues related to safety, fuel processing requirements, attentiveness to fueling, ease of control, ability to use a range of fuels or pots, exposure of user to waste heat, and stove durability. In the light of this argument, the *Heterogeneous Testing Protocol* was developed and documented to cover and address most of the key facets suggested by Taylor for future study. Selected examples, backed up with laboratory data and results from the evaluation of fuel/stove combinations, have been presented in this thesis to substantiate arguments for the inclusion of certain parameters in the protocols. For example, the SeTAR Centre *HTP* "…*has made a compelling case for the use of tests that provide performance data over a wide range of use scenarios, the equivalent of providing* ***performance curves*** *for pumps rather than the minimum and maximum performance points*." (Taylor 2009:66).

Through a set of illustrative examples, it was shown that the hypothesis is true; that the *Heterogeneous stove Testing Protocol provides* a better representation of thermal performance and emissions than existing protocols based on prescribed fuels and fuel loads, and single tasks. Through comprehensive, quantitative evaluation of gas emissions in an internally consistent manner, the *HTP* has been demonstrated to provide a robust measure of performance evaluation of a diverse range of stove and fuel combinations for Clean Development Mechanism and Gold Standards inter comparison and certification purposes.

5.3 Recommendations and Areas of Further Research

In as much as it has been demonstrated, for a variety of fuel/stove combinations, that the *Heterogeneous stove Testing Protocol* provides a valuable tool for the assessment of stove performance, it is noted that these tests were wholly lab-based. However, laboratory tests alone are insufficient for the development of robust stove testing and overall assessment of fuel/stove combinations. Laboratory tests serve a useful purpose in comparing relative performance of different stoves under similar conditions. To promote a better understanding of real-world emissions, in-field evaluations of fuel/stove combinations are needed to identify the critical conditions and variables governing emissions, and to validate that the laboratory tests are indeed emulating these. Thus there is a need for the *HTP* to be evaluated against in-field assessments of a variety of fuel/stove combinations to assess how closely it simulates real world uses. This is an area in which further research needs to be carried out.

The *HTP* could be adapted to performance evaluation of a variety of fuel/stove/pot combinations in what has been termed the *Uncontrolled Cook Test* (UCT) (Robinson *et al*., 2011). The UCT is a low-cost field testing protocol that assesses the task-based performance of the system (fuel/stove/pot combination) while a householder cooks a meal as per local conditions and practice. This method has a potential to offer a quick and effective way of assessing the energy savings delivered by a new technology as part of a carbon-offset or development programme (Robinson *et al*., 2011).

Other research avenues include:

- The design and construction of a dilution system for particulate matter for use in the determination of particulate emission performance of a variety of fuel/ stove combinations.
- The examination of emission and thermal characteristics of wood-burning devices using the *Heterogeneous stove Testing Protocol*.
- Presentation of the *Heterogeneous stove Testing Protocol* to the Global Alliance for Clean Cookstoves as a standard protocol; and identifying ways to have the Protocol certified and accredited by organisations such as ASTM and TÜV Rheinland.
- Refining of the *Heterogeneous stove Testing Protocol* taking into consideration the findings of this study.
- Application of the *Heterogeneous stove Testing Protocol* in programmes of safer, energy efficient stove development in South Africa and elsewhere.

References

Ahuja, D. R., J. Veena, K. R. Smith, C. Venkataraman (1987), Thermal performance and emission characteristics of unvented biomass-burning cookstoves: A proposed standard method for evaluation, *Biomass, 12*, 247-270.

Alvarez, D., C. Palma, M. Tay (2004), Evaluation of improved stove programmes in Guatemala: Report of project case studies, ESMAP Technical paper No. 060, The World Bank Group, Washington, DC.

Anderson, P.S. (2011), TLUD stoves in 2011: Within a classification of stoves, *ETHOS Conference*, Seattle-Kirkland, WA, 28-30 January 2011.

Andreae, M. O. (1991), Biomass burning: Its history, use and distribution and its impact on environmental quality and global climate, in *Global Biomass Burning*, edited by J. S. Levine, pp. 3-28, Cambridge, MA.

Annegarn, H. J., C. Pemberton-Pigott, T. V. Molapo, D. Milosavljevic, C. Cook (2009), Combustion emissions testing and combustion stove development at the SeTAR Centre, Central Energy Fund (CEF) BnM Task Team Workshop, Johannesburg, 22 June 2009.

Annegarn, H. J. (2006), Implications of the new air quality act for the residential built environment, *Environmental Management*, *37*, 18-21.

Annegarn, H. J., J. S. Sithole (1999), Soweto Air Monitoring Project (SAM), Quarterly Report to the Department of Minerals and Energy, Report No. AER 20.001 Q-SAM, University of Witwatersrand, Johannesburg.

Bailey, D. S., R. L. Smith, P. A. Araman (2004), An analysis of the physical properties of recorded CCA-treated wood from residential decks, *Wood and Fibre Science, 36*(2), 278-288.

Bailis, R., K. R. Smith, R. Edwards (2004), The kitchen performance test Version 1.5, Technical Report, Household Energy and Health Programme, Shell Foundation, London.

Bailis, R., V. Berrueta, C. Chengappa, K. Duta, R. Edwards, O. Masera, D. Still, K. R. Smith (2007a), Performance testing for monitoring improved biomass stove interventions: Experience of the household energy project, *Energy for Sustainable Development, XI*(2), 57-70.

Bailis, R., D. Ogle, N. MacCarty, D. Still, R. Edwards, K. R. Smith (2007b), The Water Boiling Test Version 3.0: Cookstove emissions and efficiency in a controlled laboratory, Technical Report, University of California, Berkley.

Baldwin, S. F. (1987), *Biomass Stoves: Engineering Design, Development, and Dissemination*, Volunteers in Technical Assistance (VITA), Arlington, VA.

Ballard-Tremeer, G., H. H. Jawurek (1996), Comparison of five rural, wood-burning cooking devices: efficiencies and emissions, *Biomass and Bioenergy, 11*(5), 419-430.

Ballard-Tremeer, G., H. H. Jawurek (1999), Evaluation of the dilution chamber method for measuring emissions of cooking devices, *Biomass and Bioenergy, 17*, 481-494.

Ballard-Tremeer, G. (1997), Emissions of rural wood-burning cooking devices, PhD thesis, University of Witwatersrand, South Africa.

Balmer, M. (2007), Household coal use in an urban township in South Africa, *Journal of Energy in Southern Africa, 18*, 27-32.

Barnes, B., A. Mathee, E. Thomas, N. Bruce (2009), Household energy, indoor air pollution, and child respiratory health in South Africa, *Journal of Energy in Southern Africa, 20*(1), 4-13.

Barnes, B., A. Mathee, L. Krieger, L. Shafritz, M. Favin, L. Sherburne (2004), Testing selected behaviours to reduce indoor air pollution exposure in young children, *Health Education Research, 19*(5), 543-550.

Barnes, D. F., W. Floor (1999), Biomass energy and the poor in the developing countries, *Journal of International Affairs, 53*(1), 237-259.

Barnes, D. F. (2006), Clean household energy and indoor air pollution, U.S. Japan Bilateral Workshop on Climate Change, Energy and Water Development, The World Bank, Washington, DC, 22-23 March 2006.

Barnes, D. F., K. Openshaw, K. R. Smith, R. van der Plas (1994), What makes people cook with improved biomass stoves? A comparative international review of stove programs, The World Bank Technical Paper No. 242, The World Bank, Washington, DC.

Barnes, B. R. (2005), Interventions to reduce child indoor air pollution exposure in developing countries: Behavioural opportunities and research needs, *Children, Youths and the Environment, 15*, 67-82.

Barnes, D. F., K. Kutrilla, W. F. Hyde (2005), *The Urban Household Energy Transition: Social and Environmental Impact in the Developing World*, Resources for the Future, Washington, DC.

Bautista, L. E., A. Correa, J. Baumgartner, P. Breysse, G. M. Matanoski (2009), Indoor charcoal smoke and acute respiratory infections in young children in the Dominican Republic, *American Journal of Epidemiology, 169*(5), 572-580.

Beck, E. (2009), Project Chulha. <www.designobsever.com > (Accessed August 24, 2009)

Belonio, A. T. (1993), Cookstove initiatives on production, promotion and commercialization: The CPU experience, Consultation Meeting on the Formulation of a National Cookstove Program, Silliman University, Dumaguete City, 3-5 November, 1993.

Berntsen, T., J. Fuglestvedt, G. Myhre, F. Stordal, T. F. Berglen (2006), Abatement of greenhouse gases: Does location matter? *Climatic Change, 74*, 377-411.

Berrueta, V. M., R. D., Edwards, O. R. Masera (2008), Energy performance of wood-burning cookstoves in Michoacán, Mexico, *Renewable Energy, 33*, 859-870.

Bhattacharya, S. C., A. H. Siddique, H. L. Pham (1999), A study on wood gasification for low-tar gas production, *Energy, 24*, 285-296.

Bhattacharya, S. C., D. O. Albina, P.A. Salam (2002), Emission factors of wood and charcoal-fired cookstoves, *Biomass and Bioenergy, 23*, 453-469.

Behrens, A. (1986), Total energy consumption by Brazilian households, *Energy, 11*, 607-611.

Bialy, J. (1991), Evaluation criteria for improved cookstove programmes: The assessment of fuel savings, Project Background Report No. 2, Environment and Policy Institute, East-West Centre, Hawaii.

Bokhary, A. Y., G. M. Zaki, A. M. Al-Turki (2002), Safe and environment friendly wood fuelled cooking stove in Hajj camps, *The 6th Saudi Engineering Conference, Vol. 5*, Dhahran, Saudi Arabia, December 2002, pp. 563-575.

Bond, T. (2007), Proposal for ETHOS Technical Committee on Stove Testing Methods. <www.bioenergylists.org/ethos_tc> (Accessed November 29, 2010)

Boy, E., N. Bruce, K. R. Smith, R. Hernandez (2000), Fuel efficiency of an improved wood-burning stove in rural Guatemala: Implications for health, environment and development, *Energy for Sustainable Development, IV*, 23-31.

Bradnum, C. (2007), A study of domestic paraffin stove design factors, MTech thesis, University of Johannesburg.

Bruce, N., R. Perez-Padilla, R. Albalak (2000), Indoor air pollution in developing countries: A major environmental and public health challenge, *Bulletin of the World Health Organization 78*, 1078-1092.

Bruce, N., E. Bates, R. Nguti, S. Gitonga, J. Kithinji, A. Doig (2002), Reducing indoor air pollution through participatory development in rural Kenya, *Indoor Air, 12*, 590-595.

BS 3841:1972, Standard method for the measurement of smoke from manufactured solid fuels for domestic open fires, British Standards Institution, London.

Bussmann, P. (1988), Woodstoves: Theory and applications in developing countries, PhD thesis, Eindhoven University of Technology, The Netherlands.

Bussmann, P., K. Krishna Prasad, F. Sulilatu (1985), On the testing of wood burning cookstoves, *Proceedings of the 3rd EC Conference on Energy for Biomass*, edited by W. Palz, J. Cooms, D. O. Hall, Elsevier, London.

Bussmann, P., P. Visser, K. Krishna Prasad (1983), Open fires: Experiments and Theory, in *Wood Heat Cooking*, edited by Krishna Prasad, K., P. Verhaart, Indian Academy of Science, Bangalore.

Butcher, S. S., U. Rao, K. R. Smith, J. Osborn, P. Azuma, H. Fields (1984), Emission factors and efficiencies for small-scale open biomass combustion: Toward standard measurement techniques, *Annual Meeting of the American Chemical Society*, Philadelphia PA, 26-31 August 1984. <http://www.anl.gov/PCS/acsfuel/preprint%20archive/Files/29_6_PHILADELPHIA_08-84_0122.pdf> (Accessed September 16, 2009)

Chen, Y., G. Zhi, Y. Feng, D. Liu, G. Zhang, J. Li, G. Sheng, J. Fu (2009), Measurements of black and organic carbon emission factors for household coal combustion in China: Implication for emission reduction, *Environmental Science and Technology, 43*(24), 9495-9500.

Claus, J., W. F. Sulilatu, M. Verwoerd (1982), Performance of the Tungku Lowon woodstove, Eindhoven University of Technology and TNO, Apeldoorn, Netherlands.

Davidson, C., J. E. Borrazzo, C. T. Hendrickson (1986), Pollutant emission factors for gas stoves: A literature survey, U.S. EPA Report No. CR-812543-0-0, Environmental Protection Agency, Research Triangle Park, NC.

Davis, M. (1998), Rural household energy consumption: The effects of access to electricity-evidence from South Africa, *Energy Policy, 26(3)*, 207-217.

De Lepeleire, G., K. K. Prasad, P. Verhaart, P. Visser (1981), *A Woodstove Compendium*, Eindhoven University of Technology, Eindhoven, The Netherlands.

De Wet, T., A. Mathee, B. Barnes (2001), Anthropology and epidemiology: A case study of health and environment in Alexandra, Johannesburg, *Africanus, 31*, 75-106.

Devine, S., S. Kirkley, C. Palumbo, R. White (2002), MRI and neuropsychological correlates of carbon monoxide exposure: A case report, *Environmental Health Perspectives, 110*, 1051-1055.

DME (2004), Integrated Household Clean Energy Strategy Prospectus. <http://cdm.unfccc.int/filestorage/P/0/M/P0MJ3E526AG9OTS4YX7DFKRCHWLI81/Enclosure%206.pdf?t=RXR8MTMwNzM2NTM2OS44Mw==|9f3Fp7kIJa7qw7RB1ux5IWGLofU> (Accessed June 06, 2011).

DNES (1988), A publication on improved chulhas, Field Document No. 14, Ministry of Non-Conventional Energy Sources, Government of India, New Delhi, pp. 8-16.

Duta, K., K. N. Shields, R. Edwards, K. R. Smith (2007), Impact of improved biomass cookstoves on indoor air quality near Pune, India, *Energy for Sustainable Development, XI*(2), 19-32.

Dutt, G., N. H Ravindranath (1993), Alternative bio-energy strategies for cooking, in *Renewable Energy: Sources for Fuels and Electricity*, edited by T. B. Johansson, H. Kelly, A. K. N. Reddy, R. H. Williams, Island Press, Washington, DC.

Eckholm, E., G. Foley, G. Barnard, L. Timberlake (1984), *Fuelwood: The Energy Crisis That Won't Go Away*, Earthscan, International Institute for Environmental and Development, London.

Edwards, R. D., K. R. Smith, J. Zhang, Y. Ma (2003), Models to predict emissions of health-damaging pollutants and global warming contributions of residential fuel/stove combinations, *Chemosphere*, *50*, 201-215.

Edwards, R. D., K. R. Smith, J. Zhang, Y. Ma (2003), Implications of changes in household stoves and fuel use in China, *Energy Policy, 32*, 395-411.

Ellegard, A. (1996), Cooking fuel smoke and respiratory symptoms among women in low-income areas in Maputo, *Environmental Health Perspectives, 104*(9), 980-985.

Engelbrecht, J. P., L. Swanepoel, M. Zunckel, J. C. Chow, J. G. Watson, R. T. Egami (1999) Modelling PM10 aerosol data from the Qalabotjha low smoke fuels macro-scale experiment in South Africa, *Ecological Modelling, 127*, 235-244.

EPA (2005), Climate Leaders Greenhouse Gas Inventory Protocol: Design Principles, U.S. Environmental Protection Agency, Research Triangle, NC. <www.epa.gov/climateleaders> (Accessed February 25, 2011).

EPA (2007), Guidance for Preparing Standard Operating Procedures (SOPs), U.S. Environmental Protection Agency (EPA) QA/G-6, Office of Environmental information, Washington, DC.

Ezzati, M., B. M. Mbinda, D. M. Kammen (2000), Comparison of emissions and residential exposure from traditional and improved cookstoves in Kenya, *Environmental Science and Technology, 34*, 578- 83.

Ezzati, M., D. Kammen (2002), Evaluating the health benefits of transitions in household energy technologies in Kenya, *Energy Policy, 30*, 815-826.

FAO (1987), Simple techniques for charcoal making, *FAO Forestry Paper 41*, Food and Agricultural Organisation of the United Nations, Rome.

FAO (1998), Guidelines for quality management in soil and plant laboratories, *FAO Soils Bulletin 74*, Food and Agricultural Organisation of the United Nations, Rome.

FEMA (1999), Guide to developing effective standard operating procedures for fire and EMS Departments, Federal Emergency Management Agency, United States Fire Administration, Washington, DC.

Floor, W., R. van der Plas (1992), CO_2 Emissions by the residential sector: Environmental implications of inter-fuel substitution, Energy Series Working Paper 51, Industry and Energy Department, The World Bank, Washington, DC.

Foley, G. (1986), Charcoal making in developing countries, Technical Report No. 5, International Institute for Environment and Development, London.

Foley, G. (1995), Photovoltaic applications in rural areas of the developing world, Energy Series Technical Paper No. 304, The World Bank, Washington, DC.

Foley, G., P. Moss (1983), Improved cooking stoves in developing countries, Technical Report No. 2, Earthscan, London.

Funk, P.A. (2000), Evaluating the international standard procedure for testing solar cookers and reporting performance, *Solar Energy*, *68*(1)*,* 1-7.

Government Gazette (2009), National Ambient Air Quality Standards, *Government Gazette No. 32816*, *534*, 1-9, Government Printer, Pretoria.

Granderson, J., J. S. Sandu, D. Vasquez, E. Ramirez, K. R. Smith (2009), Fuel use and design analysis of improved wood-burning cookstoves in the Guatemala highlands, *Biomass and Bioenergy, 33*, 306-315.

Heltberg, R. (2005), Factors determining household fuel choice in Guatemala, *Environment and Development Economics*, *10*(3), 337-361.

Heltberg, R. (2001), Determinants and impact of local institutions for common resource management, *Environment and Development Economics*, *6*(2), 183-208.

Hildemann, L. M., G. R. Markowski, M. C. Jones, G. R. Cass (1991), Emissions from boilers, fireplaces, automobiles, diesel trucks, and meat-cooking operations, *Aerosol Science and Technology, 14*, 138-152.

Holzmann, G. J. (1992), Protocol design: Redefining the state of the art, *IEEE Software, 9*, 17-22.

Howells, M. I., T. Alfstad, D. G. Victor, G. Goldstein, U. Remme (2005), A model of household energy services in a low-income rural African village, *Energy Policy, 33,* 1833-1851.

IS 4246 (2002), Specification for domestic gas stoves for use with liquefied petroleum gas, Bureau of Indian Standards (BIS), New Delhi.

Islam, N. R. (1980), Study of the problems and prospects of biogas technology as a mechanism for rural development: Study in a pilot area of Bangladesh, International Development Research Centre, Ottawa.

Islam, N. R., K. R. Smith (1989), Combustion test results on lignite briquettes, *Third Coal Research Conference*, Wellington, New Zealand, October 1989.

Jetter, J. J., P. Kariher (2009), Solid-fuel household cook stoves: Characterisation of performance and emissions, *Biomass and Bioenergy, 33*, 294-305.

Johnson, M., R. Edwards, A. Ghilardi, V. Berrueta, O. Masera (2007), Why current assessment methods may lead to significant underestimation of GHG reductions of improved stoves, *Boiling Point, 54*, 11-14.

Johnson, M., R. Edwards, C. A. Frenk, O. Masera (2008), In-field greenhouse gas emissions from cookstoves in rural Mexican households, *Atmospheric Environment, 42*, 1206-1222.

Johnson, M., R. Edwards, V. Berrueta, O. Masera (2010), New approaches to performance testing of improved cookstoves, *Environmental Science and Technology, 44*, 368-374.

Joshi, V., C. Venkataraman, D. R. Ahuja (1989), Emissions from burning bio-fuels in metal cookstoves, *Environmental Management, 13*(6), 763-772.

Joshi, V., C. Venkataraman, D. R. Ahuja (1991), Thermal performance and emission characteristics of biomass-burning heavy stoves with flues, *Pacific and Asian Journal of Energy, 1*, 1-19.

Kaoma, K. G. B. (1994), Efficiency and emission of charcoal use in the improved *mbuala* cookstove, Stockholm Environment Institute, in collaboration with SIDA, Stockholm.

Karademir, A. (2006), Evaluation of the potential air pollution from fuel combustion in industrial boilers in Kocaeli, Turkey, *Fuel*, *85*(12-13), 1894-1903.

Karekezi, S. (1992), The role of a stoves information network in addressing the indoor air pollution issue: An African perspective, in *Indoor Air Pollution from Biomass Fuel - Working papers from a WHO Consultation*, World Health Organisation, Geneva, pp. 91-103.

Karekezi, S., L. Majoro (2002), Improving energy services for Africa's urban poor, *Energy Policy*, *30*, 1015-1028.

Kayal, T. K., M. Chakravarty, G. K. Biswas (1994), Mathematical modelling of continuous updraft gasification of bundled jute stick – a low ash content woody biomass, *Bio-resource Technology*, *49*, 61-73.

Khummongkol, D., W. Arunlaksadamrong (1990), Performance of an updraft mangrove wood gasifier, *Energy*, *15*, 781-784.

Kishore, V., P. Ramana (2002), Improved cookstoves in rural India: How improved are they?: A critique of the perceived benefits from the national programme on improved Chulhas (NPIC), *Energy*, *27*, 47–63.

Kituyi, E., L. T. Marufu, B. Huber, S. O. Wandinga, I. O. Jumba, M. O. Andeae, G. Helas (2001), Biofuel consumption rates and patterns in Kenya, *Biomass and Bioenergy*, *20*, 83-99.

Krugmann, H. (1987), Review of issues and research relating to improved cookstoves, Report No. IDRC-MR152e, The International Development Research Centre (IDRC), Ottawa.

Kshirsagar, M. P. (2009), Experimental study for improving energy efficiency of a charcoal stove, *Journal of Scientific and Industrial Research*, *68*, 412-416.

Kuhnhem, K. (2003), Environmental and socio-economic impact of improved stoves – The case of the Tsotso stove in Northern Namibia, MSc thesis, Lund University, Sweden.

Le Roux, L. J., M. Zunckel, S. McCormick (2009), Reduction in air pollution using the '*basa njengo magogo*' method and the applicability to low-smoke fuels, *Journal of Energy in Southern Africa*, *20*(3), 3-10.

Leach, G., M. Gowen (1987), Household energy handbook: An interim guide and reference manual, World Bank Technical Paper No. 67, The World Bank, Washington, DC.

Lionel, T., R. J. Martin, N. J. Brown (1986), A comparative study of combustion in kerosene heaters, *Environmental Science and Technology*, *20*, 78-85.

Liu, K., J. Yang, Y. Wang (2008), Desulphurization of coal via low temperature atmospheric alkaline oxidation, *Chemosphere*, *71*(1), 183-188.

Lloyd, P. J. D., E. F. Visagie (2007), The testing of gel fuels and their comparison to alternative cooking fuels, *Proceedings of the 15th Domestic Use of Energy (DUE) Conference*, Cape Peninsula University of Technology, Cape Town. <www.erc.uct.ac.za/Research/publications/07Lloyd%20Visagie%20fuels.pdf> (accessed on 27 September, 2010)

Lloyd, P. (2002), The safety of paraffin and LPG appliances for domestic use, *Energy Management Use, 8*(2), 1-6.

Ludwig, L., T. L. Marufu, B. Huber, M. O. Andreae, G. Helas (2003), Domestic combustion of biomass fuels in developing countries: A major source of atmospheric pollutants, *Journal of Atmospheric Chemistry*, *44*, 23-37.

MacCarty, N., D. Ogle, D. Still (2010), Fuel use and emissions of fifty cooking stoves in the laboratory and related benchmarks of performance, *Energy for Sustainable Development*, *14*, 161-171.

MacCarty, N., D. Ogle, D. Still, T. Bond, C. Roden (2008), A laboratory comparison of the global warming impact of five major types of biomass cooking stoves, *Energy for Sustainable Development, XII*(2), 5–14.

Macumber, D. W., D. R. Jaasma (1982), Efficiency and emissions of a hand-fired residential coal stove, *Proceedings of the 1981 International Conference on Residential Solid Fuels, Environmental Impacts and Solutions*, edited by J. A. Cooper, D. Malek, Oregon Graduate Centre, OR, pp. 873-880.

Madubansi, M., C. M. Shackleton (2006), Changing energy profiles and consumption patterns following electrification in five rural villages, South Africa, *Energy Policy, 34*(18), 4081-4092.

Madubansi, M., C. M. Shackleton (2007), Changes in fuelwood use and selection following electrification in the Bushbuckridge Lowveld, South Africa, *Journal of Environmental Management*, *83*, 416-426.

Makonese, T., J. Robinson, C. Pemberton-Pigott, H. J. Annegarn (2010a), South African paraffin stoves: A comparative analysis of thermal and emissions performance, *National Association of Clean Air (NACA) Annual Conference*, Polokwane, South Africa, 13-15 October 2010.

Makonese, T., J. Robinson, D. K. Kimemia, T. V. Molapo, H. J. Annegarn (2010b), Domestic combustion of solid fuels: The need for heterogeneous testing protocols for thermal and emissions performance, *People's Energy Network (PEN) Conference*, Botswana, Gaborone, Botswana, 20-22 October 2010.

Makonese, T., Robinson, J., Pemberton-Pigott, C., Molapo, V. H. J. Annegarn (2010c), A *heterogeneous* testing protocol for certifying stove thermal and emissions performance for GHG and air quality management accounting purposes, *AWMA International Specialty Conference: Leapfrogging Opportunities for Air Quality Improvement*, Xi'an, China, 10-14 May 2010.

Marufu, T. L., J. Ludwig, M. O. Andreae, J. Lelieveld, G. Helas (1999), Spatial and temporal variation in domestic biofuel consumption rates and patterns in Zimbabwe: Implications for atmospheric trace gas emission, *Biomass and Bioenergy*, *16*, 311-332.

Masera, O. R., B. D. Saatkamp, D. M. Kammen (2000), From linear fuel switching to multiple cooking strategies: A critique and alternative to the energy ladder model, *World Development*, *28*(12), 2083-2103.

Masera, O. R., R. Diaz, V. Berrueta (2005), From Cookstoves to Cooking Systems: the integrated program on sustainable household energy use in Mexico, *Energy for Sustainable Development, XI*(1), 25-36.

McCrillis, R. C., P. G. Burnet (1990), Effects of burn-rate, wood species, altitude and stove type on woodstove emissions, *Toxicology and Industrial Health, 6*(5), 95-102.

Mitra, A. P., L. Morawska, C. Sharma, J. Zhang (2002), Chapter two: Methodologies for characterization of combustion sources and for quantification of their emissions, *Chemosphere, 49*, 903-922.

MNES (1993), Annual Report 1992-1993, Ministry of Non-conventional Energy Sources, Government of India, New Delhi.

Muller, E., R. D. Diab, M. Binedall, R. Hounsome (2003), Health risk assessment of kerosene usage in an informal settlement in Durban, South Africa, *Atmospheric Environment, 37*, 2015-2022.

Murray, C., A. Lopez (1996), *Global Burden of Disease*, Harvard University Press, Cambridge, MA.

Murray, M. J. (2009), Fire and ice: Unnatural disasters and disposable urban poor in post-apartheid Johannesburg, *International Journal of Urban and Regional Research, 33*(1), 165-192.

Nangale G. F. (1992), Stove emission monitoring, *Boiling Point, 28*, 15-18.

National Treasury (2009), Municipal Financial Management Act No. 56 of 2003, Department of National Treasury, Pretoria.

Nussbaumer, T., C. Czasch, N. Klippel, L. Johansson, C. Tullin (2008), Particulate emissions from biomass combustion in IEA countries: Survey of measurements and emission factors, IEA Bionenergy Task 32. <www.ieabcc.nl> (accessed on 26 September, 2010).

Nuwarinda, H. (2007), Air pollution study of a Highveld township during a *Basa njengo Magogo* rollout, MSc dissertation, University of Johannesburg.

Olalusi, A., O. B. Bolaji (2009), Development of an improved coal stove for cooking in developing countries, *AU J. T. 12*(13)*,* 182-187.

PD 6434 (1969), Recommendations for the design and testing of smoke reducing solid fuel burning domestic appliances, British Standards Institution, London.

Panwar, N. L. (2010), Performance evaluation of developed domestic cookstove with Jatropha shell, *Waste Biomass Valorization, 1*(3), 309-314.

Pemberton-Pigott, C., H. J. Annegarn, C. Cook (2009), Emission reductions from domestic coal burning: Practical application of combustion principles, *Proceedings of the Domestic Use of Energy (DUE) Conference 2009*, Cape Peninsula University of Technology, Cape Town, 14-16 April 2009, 8 pp.

Pennise, D. M., K. R. Smith, J. P. Kithinji, M. E. Rezende, J. J. Raad, J. Zhang, C. Fan (2001), Emissions of greenhouse gases and other air borne pollutants from charcoal making in Kenya and Brazil, *Journal of Geophysical Research, 106*(D20), 143-155.

Pesambili, C., F. Magessa, N. Mwakabuta (2003), Sazawa charcoal stove designed for efficient use of charcoal, *International Conference on Industrial Design Engineering UDSM*, Dar Es Salaam, 17-18 July 2003.

PDC (2004), Implementation of Basa njengo Magogo (BnM) technology, Department of Minerals and Energy, Pretoria. Report available on <www.dme.gov.za/energy/coal.stm> (Accessed October 13, 2009).

Pope, A., R. Burnett, M. Thun, E. Calle, D. Krewski, I. Kazuhiko, G. Thurston (2002), Lung cancer, cardiopulmonary mortality and long term exposure to fine particulate air pollution, *JAMA, 287*(9), 1132-1141.

Prasad, K. (1983), Wood-burning stoves: Their technology, economics and deployment, Working Paper for the World Employment Programme Research, International Labour Organisation, Geneva.

Prasad, K. K., E. Sangen, P. Visser (1985), Wood-burning cookstoves, *Advances in Heat Transfer*, *17*, 159-317.

Prasad, K., E, Sangen, M. Sielken, P. Visser (1983), Test results on kerosene and other stoves, WSG, Eindhoven University of Technology, Eindhoven.

Rani, C. S., T. C. Kandpal, S. C. Mullick (1992), Preliminary study of water boiling test procedures used for performance evaluation of fuelwood cookstoves, *Energy Conversion and Management, 33*(10), 919-929.

Rehfuess, E. (2006), *Fuel for Life: Household Energy and Health*, WHO Press, World Health Organization, Geneva.

Rind, D., R. Suozzo, N. K. Balachandran, M. J. Prather (1990), Climate change and the middle atmosphere 1: The double CO_2 climate, *Journal of Atmospheric Science*, *47*, 475-494.

Roberts, E., M. Wentzel (2006), Household paraffin consumption in four areas: Benoni, Galashewe, Gugulethu and Lady Grey, *Journal of Energy in Southern Africa, 17*, 23-26.

Robinson, J., M. Ibrahimo, C. Pemberton-Pigott (2011), Uncontrolled cooking test: Measuring three stone fire performance in Northern Mozambique, *Proceedings of the 19th Domestic Use of Energy Conference*, Cape Peninsula University of Technology, Cape Town, 12-13 April 2010, pp. 71-75.

Robinson, J., T. Makonese, C. Pemberton-Pigott, H. J. Annegarn (2010), Heterogeneous stove testing protocols for emissions and thermal performance, *Proceedings of the 18th Domestic Use of Energy Conference*, Cape Peninsula University of Technology, Cape Town, 29–31 March 2010, pp. 41-47.

Roden, C. A., T. C. Bond, S. Conway, A. B. O. Pinel, N. MacCarty, D. Still (2009), Laboratory and field investigations of particulate and carbon dioxide emissions from traditional and improved cookstoves, *Atmospheric Environment, 43*, 1170-1181.

Roden, C. A., T. C. Bond, S. Conway, A. B. O. Pinel (2006), Emission factors and real time optical properties of particles emitted from traditional wood-burning cookstoves, *Environmental Science and Technology, 40*, 6750-6757.

SABS 1403 (1986), Wood-burning stoves, water heaters and space heaters (reduced smoke emission type), Standard SABS 1403:Gr10, South African Bureau of Standards, Pretoria.

SANS 1906 (2009), Non-pressure paraffin stoves and heaters, Standard SANS 1906, South African National Standards, Pretoria.

Saravanakumar, A., T. M. Haridasan (2002), Feasibility on thermal cracking of wood for gasifier feed, *Bioenergy - 10th Biennial Bioenergy Conference,* Boise, Idaho, 22-26 September 2002.

Saravanakumar, A., T. M. Haridasan, T. B. Reed, R. K. Bai (2005), Operation and modelling of an updraft long-stick wood gasifier, *Energy for Sustainable Development, IX*(4), 25-39.

Scorgie, Y., C. Venter, H. J. Annegarn (2005), Air pollution over South Africa – persistent problems and emerging issues, *National Association for Clean Air (NACA) Annual Conference*, Vereeniging, September 2005.

Siwatibau, S. (1981), Rural energy in Fiji: A survey of domestic rural energy use and potential, International Development Centre, IDRC- 157e, Ottawa.

Smaller, D. (1981), The sociology of a stove, *Unasylva, 33*(134), 30-33.

Smith, K. R. (1987), *Biofuels, Air Pollution and Health*, Plenum Press, New York, pp. 79-83.

Smith, K. R. (1992), Biomass cookstoves in global perspectives: Energy, health, global warming, in *Indoor Air Pollution from Biomass Fuel - Working papers from a WHO Consultation*, WHO/PEP/92 3B, World Health Organisation, Geneva, pp. 165-186.

Smith, K. R., A. L. Aggarwal, R. M. Dave (1983), Air pollution and rural biomass fuels in developing countries: A pilot village study in India and implications for research and policy, *Atmospheric Environment, 17*(11), 2343-2362.

Smith, K. R., M. A. K. Khalil, R. A. Rasmussen, S. A. Thorneloe, F. Manegdeg, M. Apte (1993), Greenhouse gases from biomass and fossil fuel stoves in developing countries: A Manila pilot study, *Chemosphere, 26*, 479-505.

Smith K. R., R. Uma, V. V. N. Kishore, J. Zhang, V. Joshi, M. A. K. Khalil (2000a), Greenhouse implications of household stoves: An analysis for India, *Annual Reviews of Energy and Environment, 25*, 741-763.

Smith, K. R., R. Uma, V. V. N. Kishore, K. Lata, S. Madne, G. Rao, J. Zhang, R. A. Rasmussen, M. A. K. Khalil, S. A. Thorneloe (2000b), Greenhouse gases from small-scale Combustion devices in developing countries phase IIa: Household stoves in India, U.S. EPA-600/R-00-052, U.S. Environmental Protection Agency, Washington, DC.

Smith K. R. (2002), Indoor air pollution in developing countries: Recommendations for research, *Indoor Air, 12*, 198-207.

Smith K. R., K. Dutta, C. Chengappa, P. P. S. Gusain, O. Masera, V. Berrueta, R. Edwards, R. Bailis, K. N. Shields (2007), Monitoring and evaluation of improved biomass cookstove programs for indoor air quality and stove performance: Conclusions from the household energy and health project, *Energy for Sustainable Development*, *XI*(2), 5-18.

Solomon, S., G. Platther, R. Knutti, P. Friedlingstein (2009), Irreversible climate change due to carbon dioxide emissions, *Proceedings of the National Academy of Sciences of the United States of America (PNAS), 10*(6), 1704-1709.

Standish, B., A. Leiman, A. Boting, H. van Zyl (2007), Reducing the health care costs of urban air pollution: The South African experience, *Journal of Environmental Management, 84*, 27-37.

Statistics South Africa (2003), Census in brief 2001, 2nd edition, Pretoria. <www.statssa.gov.za/census01/html/CInbrief/CIB2001.pdf> (accessed on 5 November, 2009).

Stewart, B. (1987), *Improved Wood, Waste and Charcoal Burning Stoves - A Practitioners' Manual*, Intermediate Technology Publications, Southampton, London.

Stup, R. (2001), *Standard Operating Procedures: A writing guide*, Penn State College of Agriculture, Pennsylvania State University Press, Pennsylvania.

Tampleman, S. (1982), On stove diffusion in Mali, *Cookstoves News*, The Aprovecho Institute, Eugene.

Tan, Q., W. L. Chameides, D. Streets, T. Wang, J. Xu, M. Bergin, J. Woo (2004), An evaluation of TRACE-P emission inventories from China using a regional model and chemical measurements, *Journal of Geophysical Research-Atmospheres*, *109*(D22), D22305.1-D22305.21.

Taylor, P. R. (2009), The uses of laboratory testing of biomass cookstoves and the shortcomings of the dominant U.S. protocol, MSc thesis, Iowa State University, Ames, Iowa.

Terblanche, A. P., R. Nel, T. Golding (1994) Household energy sources in South Africa: An overview of the impact of air pollution on human health, CSIR and Department of Minerals and Energy, Pretoria.

Terrado, E. N., B. Eitel (2005), Pilot commercialisation of improved cookstoves in Nicaragua, ESMAP Technical Paper 085, The World Bank, Washington, DC.

Todd, J. (2001), Reducing wood-smoke through standard test methods: Lessons from Australia, *Renewable Energy, 22*, 39-44.

Trade and Industry Chamber (2004), Fund for Research into Industrial Development Growth and Equity (FRIDGE): Study to examine the potential socio-economic impact of measures to reduce air pollution from combustion, Final Report. <www.info.gov.za/aboutsa> (accessed on 27 September, 2010).

Truran, G. (2009), Household energy poverty and paraffin consumption in South Africa, *Boiling Point, 56*, 1-6.

Tschinkel, J. G., H. Tschinkel (1975), Contribution to the protection of wood fuels: Performance and economy of four types of stoves, National Forest Research Institute, Tunissien.

Tshikalanke, R. P. (2007), Spatial and temporal variation in domestic biofuel consumption rates in southern Africa, MSc dissertation, University of Witwatersrand, South Africa.

van der Plas, R. (1995), Burning charcoal issues, *Energy Issues*, The World Bank Group, Washington, DC, April 1995.

Venema, H. D., I. H. Rehman (2007), Decentralised renewable energy and the climate change mitigation-adaptation nexus, *Mitigation and Adaptation Strategy for Global Change, 12*, 875-900.

Venkata, R. P. (1996), Rural energy sector in India: An overview, *ASSET, 18*(1), 1-12.

Visser, P. (2005), The testing of cookstoves: Data of water-boiling tests as a basis to calculate fuel consumption, *Energy for Sustainable Development, XI*(1), 17-24.

VITA (1985), Testing the Efficiency of Wood-burning Cookstoves: International Standards, Volunteers in Technical Assistance, Virginia.

von Schirnding, Y. E. R., D. Yach, M. Klein (1991), Acute respiratory infections as an important cause of childhood deaths in South Africa, *South African Medical Journal, 80*, 79-82.

Wagner, N. J., P. Schoonraad, P. Swanepoel, A. van Niekerk, C. Scholtz, G. Kornelius. A. Julies, O. Pretorius, J. Wasserman, A. Muller (2005), Results of domestic smoke reduction programmes at eMbalenhle (Mpumalanga) and Zamdela (Free State), *National Association for Clean Air (NACA) Annual Conference*, Vereeniging, September 2005.

Wallenstein, T. (2003), From climate to cookstoves: An analysis of black carbon reduction policies, MSc thesis, Columbia University, NY.

Wieringa, D., C. Moore, V. Barnes (1998), *Procedure Writing: Principles and Practices*, Battelle Press, Columbus, Ohio.

Wigley, T. M. L., R. Ritchels, J. A. Edwards (1996), Economic and environmental choices in the stabilisation of atmospheric CO_2 concentrations, *Nature, 379*, 240-243.

Winkler, H., O. Davidson, A. Kenny, G. Prasad, J. Nkomo, D. Sparks, M. Howells, T. Alfstad, S. Mwakasonda, B. Cowan, E. Visagie (2006), Energy policies for sustainable development in South Africa: Options for the future, Energy Research Centre, University of Cape Town, South Africa.

WHO (1992), Indoor air pollution from biomass fuel, Report WHO/PEP/92-3A, World Health Organisaiton, Geneva.

WHO (2002a), Addressing the links between indoor air pollution, household energy and human health, *WHO-USAID Global Consultation on the Health Impact of Indoor Air Pollution and Household Energy in Developing Countries*, U.S. Agency for International Development, Washington, DC, 3-4 May 2000.

WHO (2002b), World Health Report 2002: Reducing risks, promoting healthy life, World Health Organisation, Geneva.

WHO (2006), WHO air quality guidelines for particulate matter, ozone, nitrogen dioxide, and sulphur dioxide: Global update 2005, World Health Organisation Press, Geneva. <http://www.who.int/bookorders/anglais/> (accessed 20 February, 2010).

Zeng, X., Y. Ma, L. Ma (2005), Utilization of straw in biomass energy in China, *Renewable and Sustainable Energy Reviews, 11*, 976-987.

Zhang, J., K. R. Smith, R. Uma, Y. Ma, V. V. N. Kishore, K. Lata, M. A. K. Khalil, R. A. Rasmussen, S. T. Thorneloe (1999), Carbon monoxide from cookstoves in developing countries: 1. emission factors, *Chemosphere: Global Change Science, 1*, 353–366.

Zhang, J., K. R. Smith (1999), Emissions of carbonyl compounds from various cookstoves in China, *Environmental Science and Technology, 33*(14), 2311-2320.

Zhang, J., K. R. Smith (1996), Hydrocarbon emissions and health risks from cookstoves in developing countries, *Journal of Exposure Analysis and Environmental Epidemiology, 6*, 147-161.

Zhang, J., K. R. Smith, Y. Ma, S. Se, F. Jiang, W. Qi, P. Liu, M. A. K. Khalil, R. A. Rasmussen, S.A. Thorneleo (2000), Greenhouse gases and other airborne pollutants from household stoves in China: A database for emission factors, *Atmospheric Environment, 34*, 4537-4549.

APPENDIX A: STANDARD OPERATING PROCEDURE: THE "HETEROGENEOUS STOVE TESTING PROTOCOL" (HTP) FOR THERMAL PERFORMANCE AND TRACE GAS EMISSIONS

UJ SeTAR CENTRE STANDARD OPERATING PROCEDURE

The *heterogeneous* stove testing procedure for thermal performance and trace gas emissions

SOP # 1.05
Revised December 15, 2010

SeTAR Centre
University of Johannesburg
Bunting Road Campus,
Auckland Park, 2006
Johannesburg
SOUTH AFRICA

(011) 559-4276

Prepared By: ______________________________ **Date:** ___________

Reviewed By: ______________________________ **Date:** ___________

Approved By: ______________________________ **Date:** ___________

1 GENERAL DISCUSSION

1.1 Purpose of Procedure

This standard operating procedure is intended to:

- Provide a basic understanding of the principles of stove testing.
- Describe routine operation of stove emissions performance and stove efficiency performance.
- To codify actions which are taken to determine the thermal and emissions performance of fuel/stove combinations.
- Detail quality control procedures for the reproduction of results in different tests under the same operating conditions.

This procedure is to be followed by all staff and analysts at the SeTAR Centre, University of Johannesburg.

1.2 Measurement Principle

Procedure uses mass loss and temperature gain for the determination of thermal efficiency.

TESTO® XL 350/454 uses electrochemical cells for gas measurements. CO_2 is determined using a non-dispersive infra red cell and is normally depicted as CO_2 IR. Oxygen balance is used for the calculation of excess air.

1.3 Measurements Interferences and their Minimisation

1.3.1 Water vapour interferences

Water vapour from the boiling pot will introduce a dilution effect on the flue gases compromising the results and has the potential to render ineffective the dryer on the analyser. Thus a pot should be used together with the lid it was designed for, and the lid should be equipped with a 10 mm diameter pipe protruding not more than 5 mm below the lower surface of the lid, which discharges steam outside any hood. In this way, steam from the pot will be removed from the gas stream being analysed. The pipe must always run upwards from the pot to prevent any pools of condensate from forming in the pipe. The use of pot lids is an important part of efficient cooking practice and is practised by many different cultures. Without a lid low power is not really achieved during the simmering phase (Ahuja *et al*., 1987).

1.3.2 Draft interferences

Any drafts across the test site are likely to interfere with measurements. A draft may introduce excess air in the vicinity of the stove, and it may affect the thermal and emissions performance of the stove. Tests should be conducted either in an enclosed area of shielded by wind impermeable screens.

1.4 Ranges and Typical Values of Measurements

For ranges and typical values of measurements for combustion trace gases, temperature and pressure refer to the section 1.4 of the SeTAR SOP # 2.05 Analysis of combustion trace gases using a TESTO® XL 350/454 analyser

1.5 Typical Lower Quantifiable Limits, Precision and Accuracy

(Not applicable)

1.6 Personal Responsibilities

All technicians in the laboratory carrying out this procedure are responsible for carefully reading and understanding the entire operating procedure before performing the tasks. They are also responsible for setting up for source sampling, the TESTO® XL 350/454, changing filters, un-installing equipment once testing is complete, cleaning, maintenance and calibration of instrumentation, and coding and analysing data on an EXCEL® spread sheet. The Laboratory Manager is responsible for ensuring that the procedures are properly followed for providing, storing, and recording stove and fuel samples. He is also responsible to ensure that stove and fuel samples are shipped or tested in the laboratory within the specified time period.

1.7 Definitions

No terms used in this procedure require definitions

1.8 Related procedures

SOPs related to stove testing procedures which should be read and revised in conjunction with this document are:

- SeTAR SOP # 2.05 Analysis of combustion trace gases using a TESTO® XL 350/454 analyser
- SeTAR SOP # 3.0 Calibration of TESTO® XL 350/454.

2 APPARATUS, INSTRUMENTATION, REAGENTS AND FORMS

2.1 Apparatus and Instrumentation

2.1.1 Description of the TESTO® XL 350/454 and its operational functions

The TESTO® XL 350/454 comprises a control unit, an attached box with gas analysis cells and an integrated differential pressure probe. Up to six measuring channels can be shown simultaneously on the graphic display. Up to 250 000 readings are saved for the selected location and documentation can be made on site with the integrated printer. This measurement data can be transferred to a computer via the serial interface. Readings are acquired simultaneously at several locations by decentralized loggers and/or flue gas analyzer boxes. The data is transferred to the control unit through the TESTO® data bus.

The gas analyser has an integral data logger which measures and stores the values even when not connected to the Control Unit. The analyser is equipped with four probe sockets. The following probes can be operated with the logger: temperature probes, flow velocity probes, humidity probes, gas probes, current and voltage cables, rpm probes. The logger automatically detects the probe connected to the probe socket every time the device is started.

The analyser contains the gas sensors, the measured gas and purging pumps, peltier gas preparation, gas paths, all filters, electronic evaluation and storage, the mains adapter and NIMH battery. The flue gas is drawn over the flue gas probe in the gas preparation when the gas pump is started manually or automatically. Here the measuring gas is suddenly cooled to 4-8 ºC. This precipitates the condensates with minimal absorption of NO_2 and SO_2. The dry gas passes through a particle filter, which holds back the particles. The gases then pass through the pump to the gas sensors.

The analogue output box is used to issue the analogue signals of a selection of up to 6 measuring channels in complex measuring systems consisting of loggers and analyser boxes. For this, the different components must be connected by bus lines. A maximum of two analogue output boxes can be logged onto one TESTO® databus system. The analogue outputs are current outputs, 4 to 20 mA. A load of 500Ω per output is permissible.

2.2 Instrument Characterisation

Refer to SeTAR SOP # 2.05 Analysis of combustion trace gases using TESTO® XL 350/454

2.3 Maintenance

Refer to SeTAR SOP # 2.05 Analysis of combustion trace gases using TESTO® XL 350/454

2.4 Spare Parts

Refer to SeTAR SOP # 2.05 Analysis of combustion trace gases using TESTO® XL 350/454

2.5 Equipment and apparatus

2.5.1 Digital scales

Depending on the size of the stove to be tested the size and accuracy of the digital scales will also vary. For liquid fuel/stove tests there is need to measure the fuel consumption accurately. Most paraffin stoves operating at full power use about 2g fuel per minute. Thus, one needs to measure the mass to at least 0.1g to determine the fuel consumption giving an accuracy of 73 watts. For all liquid fuel/stove tests use a 20kg digital scale with an accuracy of 0.1g. For solid fuel/stove tests 32kg digital scales with an accuracy of 1g are used giving an accuracy of 300 watts.

In most cases, the accuracy of a modern digital scale can be enhanced by accessing the internal firmware settings and by using a digital scale data capturing tool that averages the mass readings continuously. For example the DSC Tool version 1.74,by J. Pemberton-Pigott.

2.5.2 Digital thermometer

Digital thermometers with an accuracy of a $1/10^{th}$ of a degree with a thermocouple probe suitable for emissions in liquids should be used for carrying out the tests.

2.5.3 Pots

In order to optimise the comparability of the test across different types of stove we recommend that testers use two standard pots. The recommended pots are: a large pot (Hart 6.4 Litres capacity, 250 mm diameter, 125 mm height, 80% full of water) and a small pot (Hart 3.0 litres capacity, 200 mm diameter, 115 mm height, and 80% full of water). The testers should use both standard pot sizes to carry out the tests unless the stove requires a specific pot in order to function properly.

(A) 1 litre Casserole 150 mm with lid (B) 2 litre Casserole 175 mm with lid (C) 3 litre Casserole 200 mm with lid (D) 4.5 litre Casserole 225 mm with lid (E) 6 litre Casserole 250 mm with lid

Two pot sizes (**C and E**) are used in carrying out performance evaluation tests using the Heterogeneous stove Testing Protocols. The dimensions for pot **C** are as follows:

Diameter: 200 mm

Depth: 90 mm

Thickness of aluminium: 2 mm

Mass of empty pot: 435 g

Mass of lid: 101 g

The dimensions of pot **E** are as follows:

Diameter: 250 mm

Depth: 120 mm

Thickness of aluminium: 2 mm

Mass of empty pot: 680 g

Mass of lid: 192 g

2.5.4 Lids

The *heterogeneous test* should be performed with the lid on. However, there have been heated debates with regards to the use of pot lids during tests (see Annexure 1).

2.5.5 Water

Enough water should be available before carrying out the tests. There should be at least 15 litres of clean water present. In areas where water is scarce the water can be cooled and re-used in sub-sequent tests

2.5.6 Heat resistant pad

Always ensure the digital weighing scales are protected from excessive heat using resistant heat pads. If at all possible they should not be water-absorbent. To protect the digital weighing scales a heat resistant pad is placed on top of the scale and then the stove is placed upon it. The mass of the heat resistant pad should be checked before and after all tests to see if it has changed (usually indicating water loss).

2.5.7 Heat resistant gloves and gas masks

Ensure that heat resistant gloves are on hand before carrying out the tests. Use heat resistant gloves when tending the stoves during testing. Gas masks should be easily accessible in the event of carbon monoxide levels rising above recommended limits in the laboratory.

2.5.8 Lap top/ desk top for data logging

The minimum system requirements for TESTO® software include a PC with operating system Microsoft Windows 95® or higher, CD-Rom drive, Pentium 100 MHz, 32 MB Ram, 15 MB unused hard drive capacity, an available serial interface port (COM) or corresponding adapter for test 1, and USB port in a laptop or corresponding PC module for test 2. The computer is used for data logging and storage.

2.5.9 Tongs

Ensure that Tongs are present when carrying out tests involving solid fuels such as wood, charcoal and coal. Tongs are useful for handling char in solid fuel/stove tests.

2.5.10 Metal tray

A metal tray should be available for holding charcoal during fuel sorting and weighing.

2.6 Reagents

(Not applicable)

2.7 Calibration Gases

Gases used for calibration and calibration protocols are not covered in this document.

2.8 Forms and Paper Work

All fuel samples are logged into the *fuels data booklet* upon receipt at the laboratory. The laboratory Manager will create an inventory of the samples received and special instructions on handling of the samples prior to analysis. All stoves received at the Centre are recorded in the *stoves logbook* prior to analysis. The Laboratory Officer will create a *result logbook* to enter data during the experimental procedure. An example of the *result logbook* is given in the figure that follows:

SeTAR Centre's Result Log Book

Time	Weight	Fuel loss	Water Temperature	Comments
13:01:10	2572.3	0	23.6	[illegible] START [illegible]
13:02:10	2569.7	2.3	24.8	
13:03:10	2567.3	5.2	26.2	
13:04:10	2563.6	9.0	30.3	
13:05:10	2558.4	12.3	33.4	
13:06:10	2556.5	13.8	35.9	
13:07:10	2550.2	15.9	38.0	
13:08:10			41.6	
13:09:10			44.5	
13:10:10			47.8	
13:11:10			50.2	
13:12:10			53.6	
13:13:10			56.4	
13:14:10			59.3	
13:15:10			61.6	
13:16:10			64.5	
13:17:10			67.3	
13:18:10			70.2	
13:19:10			73.9	
13:20:10			76.0	

Figure 1: Example of the result logbook during emissions and performance evaluation of stoves

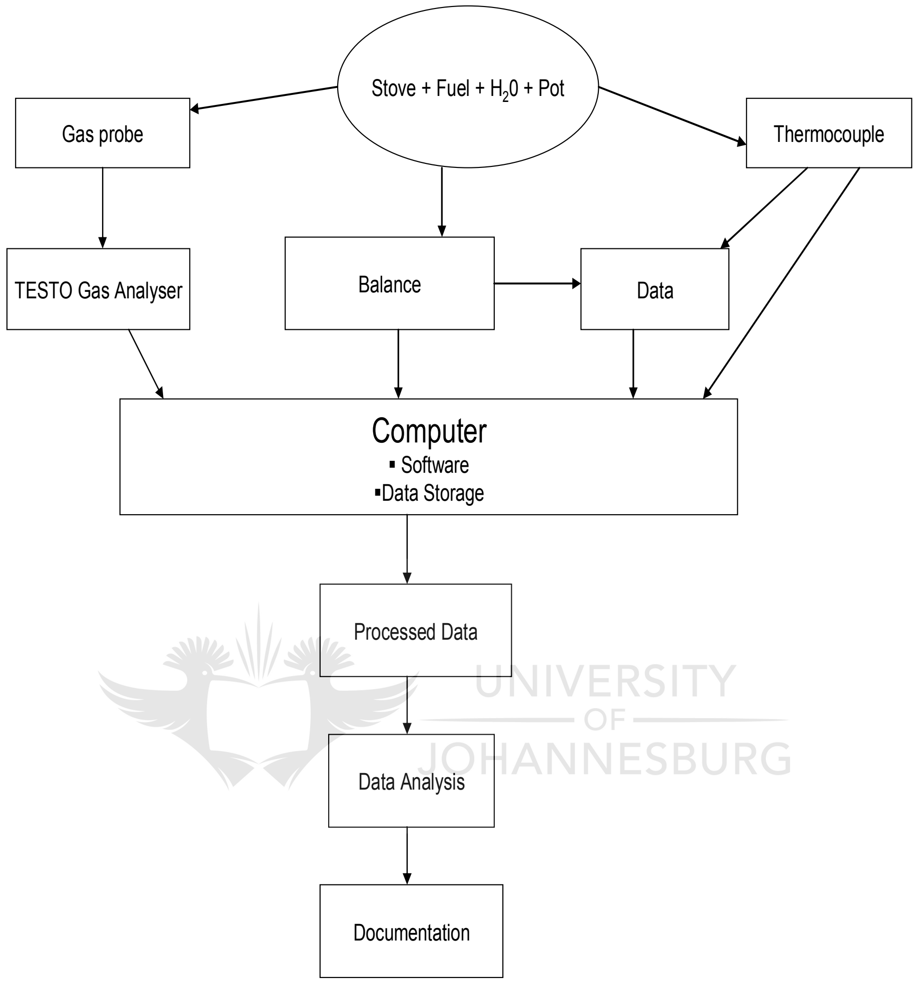
3 CALIBRATION STANDARDS

Refer to SeTAR SOP # 2.05 Analysis of combustion trace gases using TESTO® XL 350/454 for the calibration of the TESTO®

Mass balance calibration procedures are contained in their instruction manuals.

4 PROCEDURES

4.1 General Flow Diagram



4.2 Experimental procedure

4.2.1 Weigh the insulation material between the scale and the stove

4.2.2 Weigh the empty pot and lid

4.2.3 Put 5.000 Litres or 2.000 litres of water into the pot, weigh everything (Pot + Lid + water). Alternatively fill the pot to 80% of capacity and weigh the combination and record all.

4.2.4 Measure the temperature of the water by placing the plastic frame holding the thermocouple into the water, 50 mm above the bottom of the pot in the centre of its diameter.

4.2.5 Weigh the stove without the fuel and record the mass on the data sheet.

4.2.6 Weigh the fuel that will be used during the test and place it on the scale next to the stove. If it is a liquid fuel stove skip this step.

4.2.7 Fill the stove with the fuel. Measure and record the initial temperature of the fuel before lighting it up. Weigh the stove and the fuel and record the mass in the data sheet. There should be no spilled fuel on the stove that will evaporate and affect the total weight.

4.2.8 Choose an appropriately sized scale. Press ZERO to set the mass reading to 0.000 kg or 0 grammes.

4.2.9 Place the stove on the scale. It should show the mass of the stove + fuel (M0~0)

4.2.10 Start the calibrated gas analysis equipment, data logger (START TESTO®)

4.2.11 The stove should be at room temperature. Light the stove with the pot off according to the manufacturer's instructions, noting the time of ignition using a match, match extension, or using a lighting fluid such as methylated spirit as appropriate. The fire should be started in a reproducible manner according to local practices.

4.2.12 Operate the stove until the fuel consumption stabilises at the highest possible power setting available. Every 60 seconds, record the mass of the stove + the fuel. When the fuel consumption rate is stable, note the time and mass reading (M0~0) and record it in the data sheet.

4.2.13 TARE the scale and place POT1 + Water1 (M1~0) noting the time, Mass (M1~0), Time (T~11).

4.2.14 Each 60 seconds, note the temperature T~11, mass (M1~0), lift POT1 and record M2~0. (M2~0) is the mass of the fuel burned.

4.2.15 Continue with this process until the water begins to boil vigorously. Continue to record the time (T~11), (M1~0) and M2~0 after boiling if you wish.

4.2.16 Continue recording the time (T~11) and mass (M1~0) and mass of fuel lost M2~0 every 60 seconds the boiling point is reached, for 15 additional minutes.

4.2.17 Turn the power down to the midpoint between the highest and lowest power level and allow the fuel consumption to stabilise. Continue noting the temperature (T~11), pot mass (M1~0) and fuel loss mass (M2~0) if you wish. For liquid fuelled stoves this stabilisation typically takes 5 minutes.

4.2.18 Operate the stove for at least 10 minutes at this power level noting the time T~11, M1~0 and M2~0 every 60 seconds giving at least 15 sets of readings at the Medium power level.

4.2.19 Replace the pot with another filled with cold water, prepared as before. Turn down the power to the lowest sustainable level and allow fuel consumption to stabilise. Continue noting the time T~11, M1~0 and M2~0 if you wish. For liquid fuelled stoves this stabilisation typically takes 5 minutes.

4.2.20 Replace the pot with another filled with cold water prepared as before. The stove has to be operated longer on low power to get equally accurate results. Operate the stove for at least 10 more minutes on this level noting the time T~11, M1~0 and M2~0 every 60 seconds, giving at least 15 sets of readings at Low power.

4.2.21 Note the fuel temperature of the fuel and record it on the data sheet.

4.2.22 At the end of the low power readings, stop the TESTO® and measure the fuel remaining at the end of the test.

4.2.23 Save the data from the TESTO® and the scales immediately and export it all to EXCEL® data sheets for archiving and analysis.

4.3 Analyser Start-up

Refer to SeTAR SO P# 2.05 Analysis of combustion trace gases using TESTO® XL 350/454.

4.4 Routine Operation

Refer to SeTAR SOP # 2.05 Analysis of combustion trace gases using TESTO® XL 350/454.

4.5 Analyser Shut Down

Refer to SeTAR SOP # 2.05 Analysis of combustion trace gases using TESTO® XL 350/454.

4.6 Abbreviated Operational Check List

4.6.1 Starting Up

- Assemble the apparatus according to the existing SOPs.
- Zero the sensors of the gas analyser.
- Perform a fresh air rinse of the instrument. The probes are cleaned by blowing compressed air through their nozzles.
- Connect the analyser to a computer.
- Choose the measuring cycle.
- The ignition method should always be the same.
- Check to see if there are any fuel or water spills on the stove or the scales before lighting the stove.
- The stove should be placed perfectly flat on the scale and the scale should be level, as indicated on its bubble indicator.

4.6.2 Routine Operation

- Constantly check on pump flow during the experimental analysis. If it drops below 0.5 $Lmin^{-1}$, the tests has to be stopped, the machine checked and re-runs performed.
- The power setting (high, medium, and low) is always at the same level in different tests using the same fuel/stove combination.
- Check to see that the scales are functioning properly.
- The stove/pot system should be at the centre of the extraction hood during tests.
- The masses and temperatures are recorded every minute if done manually, or every 10 seconds if done automatically.

4.6.3 End Test and Analyser Shut Down

- Use Microsoft EXCEL® to store electronic data from real time measurements.
- Zero the sensors and perform a fresh air rinse of the analyser.
- Make sure all equipment has been retrieved and stored properly according to specific SOPs.
- Do not leave the site without acquiring data from any real-time monitors that may be operating at the facility (Fuel temperatures, fuel consumption, start time and end time etc).
- Clean the operational area.

5 QUANTIFICATION

(Not applicable)

6 QUALITY CONTROL

6.1 Reproducibility Testing

Tests are run several times to determine a uniform lighting method and burn cycle that's reproducible before the three definitive tests. Test runs that do not fall within the standardised cycle are rejected due to lack of Uniformity. Inconsistent results for which a reason cannot be found entails the tests to be re-run.

6.2 Daily Validation

Validation is done manually by checking the pumps before and after the analysis is performed. See SeTAR SOP # 2.05 Analysis of combustion trace gases using TESTO® XL 350/454.

6.3 Validation of Final Data File

The data is exported to an EXCEL® spread sheet for archiving and analysis. During the analysis quality control checks can be made on the data. If the data falls within the specified limits and ranges it is accepted and processed, and if the data falls outside the specified limits and range it is discarded.

7 REFERENCES

Ahuja, D.R., J. Veena, K.R. Smith, C. Venkataraman (1987), Thermal performance and emission characteristics of unvented biomass-burning cook-stoves: A proposed standard method for evaluation, *Biomass* ***12***, 247-270.

Bailis, R., D. Ogle, N. MacCarty, D. Still, R. Edwards, K.R. Smith (2007), *The Water boiling Test Version 3.0: Cook-stove Emissions and Efficiency in a Controlled Laboratory*, Technical Report, University of California, Berkley.

Baldwin, S.F. (1986), *Biomass Stoves: Engineering Design, Development, and Dissemination*, Volunteers in Technical Assistance (VITA), Arlington.

DRI SOP 2-203.1 *Anion Analysis of Filter Extracts and Precipitation Samples by Ion Chromatograp*hy, Revision No. 2, Desert Research Institute, Nevada, 1989.

DRI SOP 2-204.2 *Thermal/Optical Reflectance Carbon Analysis of Aerosol Filter Samples*, Revision No. 2, Desert Research Institute, Nevada, 1989.

DRI SOP 2-208.1 *Filter Pack Assembly, Disassembly, and Cleaning Procedure*, Revision No. 1, Desert Research Institute, Nevada, 1989.

Johnson, M., R. Edwards, V. Berrueta, O. Masera (2010), New approaches to performance testing of improved cook-stoves, *Environ. Sci. Technol.* ***44***, 368-374.

Taylor, P.R. (2009), *The Uses of Laboratory Testing of Biomass Cook-stoves and the Shortcomings of the Dominant U.S. Protocol*, MSc Thesis, Iowa State University, Ames, Iowa.

SeTAR SOP# *Analysis of Combustion Trace Gases Using TESTO® XL 350/454*, SeTAR Internal Report No. 01-10, University of Johannesburg, 2010.

8 DOCUMENTARY CHANGES

15 December, 2010: added signatures to the title page and adjusted page numbering.

Annexure 1

1. Pots: The capacity, dimensions and material of the pot have a significant influence on stove performance (Bailis *et al*., 2007). If testers use a non-standard pot, they should record the capacity, dimensions, weight, and material. However, use of non-standard pots may lead to a bias in the results and make them difficult to compare to other tests. Tests intended to predict performance in a particular community should use pots similar to those in use in that community, and should be performed with the lid on or off as common practise dictates, and this change prominently noted.
2. Lids: It is argued that the lids generally improve the performance of the stove yet the main purpose of the WBT is to quantify the way that heat is transferred from the stove to the cooking pot (Bailis et al., 2007). The approach is based on the premise that the fuel, stove and the pot (including the lid) and the operator represent the cooking system. All these factors should be optimised to improve the thermal and emissions performance of the stove. Since the lid is used for the actual cooking task, it is imperative that testers also use lids when conducting the test to simulate the actual cooking task. Open pots can complicate the test by increasing the variability of the emissions performance outcome and making it harder to compare from different tests. "*By not using a lid, evaporation rates are higher and the stove must be run at a somewhat higher power to maintain the temperature than is the case with a lid*." (Baldwin, 1986:263). Many stoves optimised for fuel efficiency will not boil a pot of water with the lid removed. We therefore recommend that the test be carried out with the lid on.

APPENDIX B: STANDARD OPERATING PROCEDURE FOR THE ANALYSIS OF COMBUSTION TRACE GASES USING A TESTO® ANALYSER

SeTAR CENTRE STANDARD OPERATING PROCEDURE

Analysis of combustion trace gases using a TESTO® XL 350/454 analyser

SOP #2.05
Revised August 16, 2010

SeTAR Centre
University of Johannesburg
Bunting Road Campus,
Auckland Park, 2006
Johannesburg
SOUTH AFRICA

(011) 559-4276

Prepared By: ______________________________ **Date:** ___________

Reviewed By: ______________________________ **Date:** ___________

Approved By: ______________________________ **Date:** ___________

1 GENERAL DISCUSSION

1.1 Purpose of Procedure

This standard operating procedure is intended to:

- Provide a basic understanding of the principles of stove testing using TESTO® XL 350/454.
- Describe routine operation of stove emissions performance using TESTO® XL 350/454 analyser.
- To codify actions which are taken to determine the thermal and emissions performance of fuel/stove combinations.
- Detail quality control procedures for the reproduction of results in different tests under the same operating conditions.

This procedure is to be followed by all staff and analysts at the SeTAR Centre, University of Johannesburg.

1.2 Measurement Principle

The TESTO® XL 350/454 is a flue gas analyser. The smallest unit capable of making measurements is the Control Unit which integrates temperature and pressure measurements. During routine operation the flue gas is drawn into the flue gas probe then passes into the gas preparation unit when the gas pump is started manually or automatically. Here the measuring gas is suddenly cooled to 4-8 ºC. This precipitates the condensation with the lowest absorption of NO_2 and SO_2. The dry gas passes through a particle filter, which holds back the particles. The gases then pass through the pump to the gas sensors. TESTO® XL 350/454 uses electrochemical cells for gas measurements. CO_2 is determined using a non-dispersive infrared cell and is normally depicted as CO_2 IR. The TESTO® uses the carbon balance to calculate excess air.

1.3 Measurements Interferences and their Minimisation

1.3.1 Water vapour interferences

Water vapour from the boiling pot has the potential to render the sensor of the analyser ineffective and should be removed or minimised from the gas stream. Ideally, the lid should be equipped with a 10 mm diameter pipe protruding not more than 50 mm below the lower surface of the lid, which discharges steam outside any hood. In this way, steam from the pot will be removed from the gas stream being analysed. The pipe must always run upwards from the pot to prevent any pools of condensate from forming in the pipe.

1.3.2 Draft interferences

Any drafts across the test site are likely to interfere with measurements. A draft may introduce excess air in the vicinity of the stove, and it may affect the thermal and emissions performance of the stove. Tests should be conducted either in an enclosed area of shielded by wind impermeable screens.

1.4 Ranges and Typical Values of Measurements

This is the concentration range in which the target gas can be measured by the sensor/unit with the specified accuracy. The typical ranges of gases collected with the TESTO® XL 350/454 are shown in the table below.

Table 1: Typical ranges of lowest gas concentrations for checking

Gas	**Lowest gas concentration**	**TESTO® Adjustment**	**Lowest gas concentration for checking**	**Detection limit**
CO	150 ppm	1 000 ppm	10 ppm	2 ppm
CO_{low}	50 ppm	300 ppm	5 ppm	0.8 ppm
NO	80 ppm	80/800 ppm	10 ppm	2 ppm
NO_{low}	40 ppm	40/300 ppm	5 ppm	0.5 ppm
H_2S	40 ppm	200 ppm	10 ppm	1 ppm
SO_2	100 ppm	1 000 ppm	10 ppm	2 ppm
NO_2	40 ppm	100 ppm	10 ppm	1 ppm
HC	4 000 ppm	5 000 ppm	4 000 ppm	100 ppm

For detailed information on ranges and typical values of measurement refer to section 8 (technical data section) of the TESTO® manual.

1.5 Typical Lower Quantifiable Limits, Precision and Accuracy

The detection limit for NO2 is ~1.9 ppm and that for NO is ~6 ppm under a nominal ranges of 0 – 3 000 ppm for NO2 and 0 – 5 000 ppm for NO. The detection limit estimates may be upwardly biased as a result of the *memory effect*. The relative accuracy obtained with low-NO_x sources indicate that, in the absence of this effect, detection limits for both NO and NO_2 are comparable to the resolution of the analyzer, i.e., 1 ppm.

For the detection limit of all the gases, refer to **Table 1**.

1.6 Personal Responsibilities

All analysts in the laboratory should read and understand this entire standard operating procedure prior to carrying out the tests.

Personnel carrying out this procedure are responsible for setting up for source sampling the TESTO® XL 350/454 for trace gas emissions performance of stoves, changing filters, un-installing equipment once testing is complete, cleaning, maintenance and calibration of instrumentation, and coding and analysing data on an Excel® spread sheet.

1.7 Definition of terms

Calibration: The determination, under prescribed conditions, of the mutual association between the indication of the analyser on the one hand and the relevant values of a variable (in this case test gas) represented as a measurement standard on the other.

Standardisation: The standardisation of a measuring device comprises the quality inspections and identification markings to be carried out in accordance with standardisation regulations (e.g.

standardisation laws, regulations on weights and measures). It is in actual fact impossible to standardise a flue gas analyser.

Reproducibility (repeat accuracy): Standard deviation of a series of measured values from measurements performed at short intervals of time and carried out according to a defined measurement procedure by the same operator on the same parts, using the same equipment and at the same place.

Zero point: What the sensor signal unit displays in the absence of the gas to be verified (= "target gas").

Slope/sensitivity: Sensor signal per admitted (unit of) concentration. This is determined in adjustment, calibration and is stored for later measurements.

Measuring range: This is the concentration range in which the target gas can be measured by the sensor/unit with the specified accuracy.

Cross-sensitivity: The characteristic of sensors to react not only to the target gas to be verified, but also to other gases.

1.8 Related procedures

SOPs related to stove testing procedures which should be read and revised in conjunction with this document are:

- SeTAR SOP # 1.05 The heterogeneous testing procedure for thermal performance and trace gas emissions.

2 APPARATUS, INSTRUMENTATION, REAGENTS AND FORMS

2.1 Apparatus and Instrumentation

2.1.1 Description of the TESTO® XL 350/454 and its operational functions

Figure 2: TESTO 350/454 M/XL portable set up, consists of a control unit, flue gas analyzer and flue gas probe.

The TESTO® 350-XL is equipped with measurement modules for O_2, CO, NO and NO_2 as standard. In addition to this, measurement modules for C_XH_Y, NO_{low}, CO_{low}, SO_2, H_2S or CO_2 by infrared module are optionally available. Parallel to the features of the S-version, the flue gas analyzer TESTO® 350-XL has a Peltier gas preparation with a peristaltic hose pump for the controlled removal of condensate as well as a fresh air valve for providing automatic zero-calibrations during long-term measurements over several hours. Both versions of the flue gas analyzer can be equipped with a maximum of up to 6 measurement modules, have as standard a built-in rechargeable battery (for mains-independent use), a measurement store (250,000 values), as well as a TESTO® databus connection.

The gas analyser has an integral data logger which measures and stores the values even when not connected to the Control Unit. The analyser is equipped with four probe sockets. The following probes can be operated with the logger: temperature probes, flow velocity probes, humidity probes, gas probes, current and voltage cables, rpm probes. The logger automatically detects the probe connected to the probe socket every time the device is started.

The analyser contains the gas sensors, the measured gas and purging pumps, peltier gas preparation, gas paths, all filters, electronic evaluation and storage, the mains adapter and NIMH battery. The flue gas is drawn over the flue gas probe in the gas preparation when the gas pump is started manually or automatically. Here the measuring gas is suddenly cooled to 4-8 ºC. This precipitates the condensation with the lowest absorption of NO_2 and SO_2. The dry gas passes through a particle filter, which holds back the particles. The gases then pass through the pump to the gas sensors.

The analogue output box is used to issue the analogue signals of a selection of up to 6 measuring channels in complex measuring systems consisting of loggers and analyser boxes. For this, the different components must be connected by bus lines. A maximum of two analogue output boxes can be logged onto one TESTO® databus system. The analogue outputs are current outputs, 4 to 20 mA. A load of 500Ω per output is permissible.

2.2 Instrument Characterisation

The TESTO® is programme driven and the data can be saved onto a PC for analysis. The measured values can be processed on a WINDOWS® GUI by means of an RS232 interface and ECONOMICAL software. The TESTO® 350/454 XL comes with a memory of 100 spot measurements which can be expanded to 400 measurements. That enables you to record large volumes of measurements even over several days.

A condensation trap integrated into the flue gas probe protects against condensation in the measuring device. The condensation trap is not sufficient for long-term measurements or for measurements in condensing furnaces and low temperature systems and can be replaced by compact gas dryers. This ensures that humid flue gas is reliably "dried". The top of-the-range version automatically pumps the condensation away.

2.3 Maintenance

2.3.1 Storage of electrochemical gas sensors

The producer of electrochemical sensors gives the advice for storage at 0 – 20°C (32 – 68°F). 30°C (86°C) and more causes of long duration dry out and speed up in losing sensitivity.

TESTO® AG gives the following advices for storage:

Storage in a fridge: Please take the daily quantity of measuring cells one day before out of the fridge, so the adaption to ambient temperature is possible.

The time of storage should be as short as possible. The age of the sensor should be not more than ½ year at fitting. You can reach this with optimisation of order quantity (minimum lot size) and recorder point.

2.3.2 Filter change

If filters are visibly dirty, they need to be changed. Replace the filter if the pump performance drops (audibly). See TESTO® instruction manual for procedures in changing filters.

2.3.3 Changing the flue gas probe

If the flue gas is heavily laden with dust, it is possible that sections of the gas path preceding the hose filter will become contaminated or blocked. For the course filter, the surface filter is easily cleaned. Minor dirt can be removed by blowing out with compressed air. For thorough cleaning, an ultrasonic bath or use of a dental prosthesis cleaner is recommended. The filter must be replaced if encrusted or damaged. (Refer to the TESTO® instruction manual on how to change filters).

2.3.4 Recalibrating with test gases

The gas sensors are factory calibrated so that they can be used in the entire measuring range. Depending on the required accuracy, the sensors can be verified, recalibrated or calibrated to restricted measuring ranges with test gas. The calibration data is stored in the sensor's electronics, not in the instrument. Verification and recalibration as necessary is recommended every six months to retain the specific accuracy of NO_2, H_2S, HC, CO $_{low}$ and CO_2i.

Ideally the test gas is applied directly to the tip of the probe to eliminate absorption in the gas path. The gas pressure must not exceed 30 hpa, ideally at zero pressure using a bypass.

2.3.5 Cleaning the pumps

Refer to the TESTO® instruction manual under section 4.1.8 on how best to clean the pumps.

Refer to the maintenance and trouble shooting guide for additional information.

2.4 Spare Parts

2.4.1 Hose set for conducting flue gas

Hoses for conducting flue gases are designed such that pressure does not develop on the measurement cell since this would lead to incorrect measurement readings. The hose is 5000 mm long and is intended to conduct flue gases away from the measuring instrument outside or to a safe place.

2.4.2 *Wall bracket analyser*

The wall bracket consists of a mounting bracket with a pipe, heat shield for analyzer box, and a lock. Under conditions of strong thermal radiation e.g. when attached directly to the flue, the heat shield is attached with clips to the handle and protects the analyser unit from excessive heating.

2.4.3 *Hood*

The hood is intended to protect the analyser box and the connected Control Unit against dirt and moisture. The hood can also be used in conjunction with wall bracket.

2.4.4 *Carrying strap set*

The carrying strap set consists of a carrying strap with two carbine hooks, two plastic clips, and a metal plate. The carrying strap can be used either for the analyser box or for individual control units.

2.4.5 *Carrying case*

The case is designed to allow the instrument to be operated whilst still in the case. However, ensure the gases can pass unobstructed from the exhaust opening. Do not close the case during measurements to allow the flue gas to dissipate.

2.4.6 *Service case*

The analyser is attached in the case by the handle. The accessory box can be clipped beneath the service case to hold further accessories.

2.5 Reagents

(Not applicable)

2.6 Gases

Recommended test gases by parameters from factory calibration of the TESTO® are presented in Table 2.

Table 2: Recommended test gases by parameters (TESTO® factory calibration)

Parameter	Test gas concentration
CO_{low}	300 ppm CO, 1.4% O_2, Rem. N_2
CO	1 000 ppm CO, 1.4% O_2, Rem. N_2
CO + CO_{low}	400 ppm CO, 300 ppm H_2, 5% O_2, Rem. N_2
NO_{low}	400 ppm, Rem. N_2 and 300 ppm NO, Rem. N_2
NO	80 ppm NO, Rem. N_2 and 800 ppm NO, Rem. N_2
NO_2	100 ppm NO_2, Rem. Synthetic air (SA)
SO_2	1 000 ppm SO_2, Rem. N_2 or SA
H2S	200 ppm H_2S, Rem. N_2 or SA
HC	5 000 ppm CH_4, Rem. SA
CO_2-IR	17% CO_2, Rem. N_2 and 40% CO_2, Rem. N_2

2.7 Forms and Paper Work

All fuel samples are logged into the *fuels data booklet* upon receipt at the laboratory. The Laboratory Manager will create an inventory of the samples received and special instructions on handling of the samples prior to analysis. All stoves received at the SeTAR Centre are recorded in the *stoves logbook* prior to carrying out performance tests on the stoves. The Laboratory Officer will create a *result logbook* to enter data during the experimental procedure.

3 CALIBRATION STANDARDS

The gases sensors are factory calibrated so that they can be used in the entire measuring range. Depending on the required accuracy, the sensors can be verified, recalibrated or calibrated to restricted measuring ranges with test gas.

For a detailed review on the calibration standards, refer to the Testo manual entitled '*Field guide: Control and adjustment of portable flue gas analysers*'. This manual can be accessed on www.testo350.com/pdfs/Inst_Man_350_Cal.pdf

4 PROCEDURES

4.1 Operational procedure

4.1.1 Connect flue gas probe

4.1.2 Insert flue gas probe in the flue gas stream.

4.1.3 Switch on the TESTO® XL 540 flue gas analyser.

4.1.4 Zero all cells (zeroing phase): temperature measurement is conducted during the zeroing phase and is interpreted by the TESTO® as the combustion air temperature and is stored as the combustion air temperature value after the zeroing phase.

4.1.5 Set fuel if necessary.

4.1.6 Perform a fresh air rinse of the instrument. The probes are cleaned by blowing compressed air through their nozzles.

4.1.7 Start the calibrated gas analysis equipment and data logger (START TESTO®)

4.1.8 Constantly check for deviations in the operation of the machine (e.g. constantly check the pump flow rate. If it drops below 0.5 L/min, the tests has to be stopped)

4.1.9 At the end of the low power readings, STOP TESTO®

4.1.10 Save the data on the TESTO® and immediately export it to an Excel® data sheet for analysis.

4.2 Analyser Start-up

The following steps outline analyser start-up:

- Connect the probe, Control unit and logger: the triple-function probe is connected to the probe socket of the Control Unit by the plug-in cable.
- Position the flue gas probe in the flue gas stream.

- Switch on the Control Unit: after the Control Unit has been switched on and a brief initialisation phase has elapsed, the readings of the connected probe and of the pressure sensor installed in the Control Unit are displayed.

4.3 Routine Operation

1. **P START** starts the measurement

4.4 Analyser Shut Down

1. **P STOP** stops the measurement

4.5 Abbreviated Operational Check List

4.5.1 Start up

- Assemble the apparatus according to the existing SOPs.
- Zero the Sensors of the gas analyser.
- Perform a fresh air rinse of the instrument. The probes are cleaned by blowing compressed air through their nozzles.
- Connect the analyser to a computer.
- Choose the measuring cycle.

4.5.2 Routine operation

- Constantly check on pump flow during the experimental analysis. If it drops below 0.5 L/min, the tests has to be stopped, the machine checked and re-runs performed.

4.5.3 End test and analyser shut down

- Store data if necessary under selected **Mem.** manual storing of individual measurements.
- Export data to an Excel® file.
- Zero the sensors and perform a fresh air rinse of the analyser.
- Do not leave the site without acquiring data from any real-time monitors that may be operating at the facility.

5 QUANTIFICATION

5.1 Calibration Procedures

The gases sensors are factory calibrated so that they can be used in the entire measuring range. Depending on the required accuracy, the sensors can be verified, recalibrated or calibrated to restricted measuring ranges with test gas. The calibration data is stored in the sensor's electronics not in the instrument.

Verification and recalibration as necessary is recommended every six months to retain the specific accuracy of NO_2, H_2S, HC, CO_{low} and CO_2i. Recalibration in the < 500ppm (with CO_2-IR < 25 Vol. %) can lead to inaccuracies in the upper measuring range.

The high quality standards of the machine are confirmed by the ISO 9001 certificate.

5.2 Calculations

Principles of calculation are presented in the TESTO® 350/454 XL manual in section 6.1.

6 QUALITY CONTROL

6.1 Performance Testing

Zero calibration is carried out automatically every time the instrument is switched on. If the analyser is used for extended periods of time it will prove necessary to repeat the zero calibration at regular intervals to neutralise any changes that occur with time. Important to note is that with time the zero point will tend to drift to a certain degree with time. Span calibration is recommended to be performed at least every six months depending on the expectations in regard to accuracy and the amount of use the analyser sees. An auto calibration for the oxygen sensors to 20.9% O2 in air is performed every time the instrument is switched on.

6.2 Reproducibility Testing

Tests are run several times to determine a uniform lighting method and burn cycle that's reproducible before the three definitive tests. Test runs that do not fall within the standardised cycle are rejected due to lack of Uniformity. Analyser anomalies include high ambient O2 measurements, under estimation of total Carbon, and under estimation of gases in the sample. Inconsistent results for which a reason cannot be found must be rerun again.

6.3 Control Charts

If the process is in control, almost all points will plot within the control limits. Any observations outside the limits, or systematic patterns within, suggest the introduction of a new (and likely unanticipated) source of variation, known as a *special-cause* variation. Since increased variation means increased *quality costs*, a control chart *signalling* the presence of a special-cause requires immediate investigation. Control charts limit *specification limits* or targets because of the tendency of those involved with the process (e.g., machine operators) to focus on performing to specification when in fact the least-cost course of action is to keep process variation as low as possible. This makes the control limits very important decision aids. The control limits tell you about process behaviour and have no intrinsic relationship to any specification targets or *engineering tolerance*.

The purpose of control charts is to allow simple detection of events that are indicative of actual process change. This simple decision can be difficult where the process characteristic is continuously varying; the control chart provides statistically objective criteria of change. When change is detected and considered good its cause should be identified and possibly become the new way of working, where the change is bad then its cause should be identified and eliminated.

Examples of control charts are presented below:

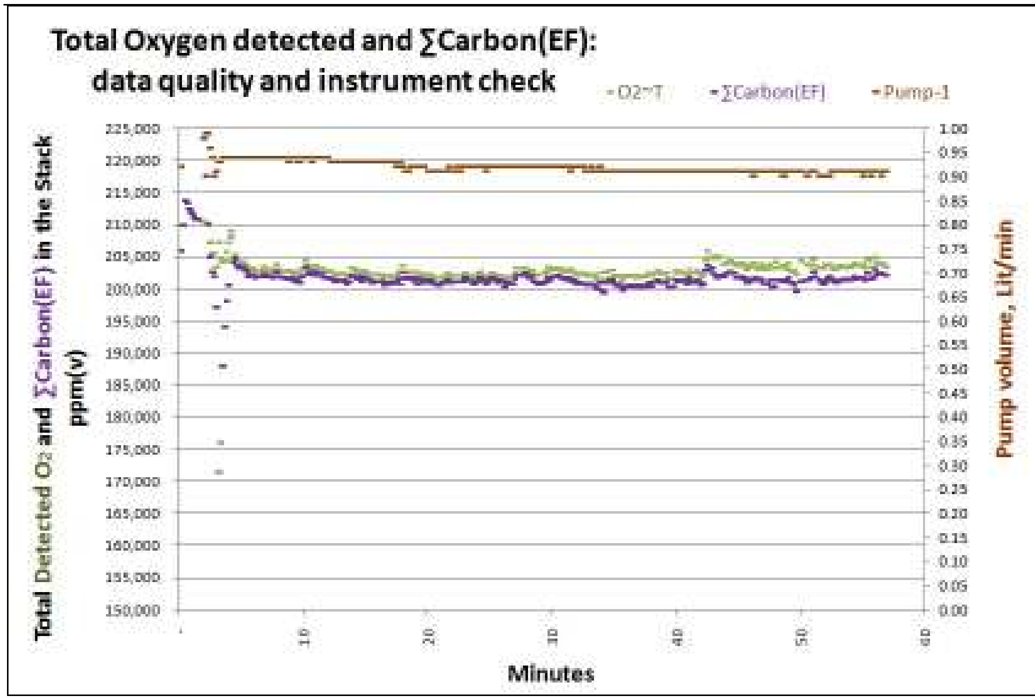


Figure 3: Example of good quality data on a control chart

(Credit: Crispin Pemberton-Pigott)

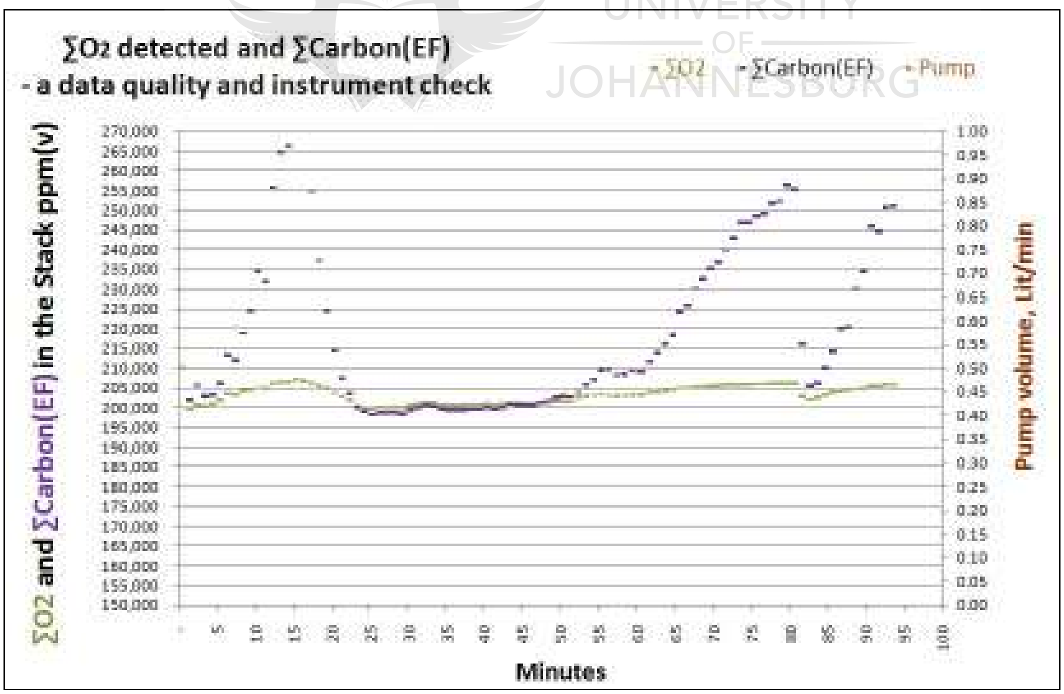


Figure 4: Example of bad quality data as shown on control charts

(Credit: Crispin Pemberton-Pigott)

6.4 Daily Validation

Validation is done manually by checking the pumps before and after the analysis is performed. Discuss any changes with the Laboratory Supervisor before taking action. If all attempts at reconciling the data fail, the suspected parameter is flagged and all supporting evidence is listed and given to the Laboratory Manager.

6.5 Validation of Final Data File

The data from the TESTO® is exported to an Excel sheet for final data validation. Data are checked for consistency, and limits and ranges are verified for quality control purposes.

7 REFERENCES

Ahuja, D.R., V. Joshi, K.R. Smith, C. Venkataraman (1987), Thermal performance and emission characteristics of unvented biomass-burning cook stoves, *Biomass* ***12***, 247–270.

DRI SOP # 2-114r7: *PM2.5 FRM Gravimetric Analysis*, Revision No. 7, Desert Research Institute, Nevada, 2010.

DRI SOP 2-208.1: *Filter Pack Assembly, Disassembly, and Cleaning Procedure*, Revision No. 1, Desert Research Institute, Nevada, 1989.

Instruction manual for TESTO® 350M/XL, Testo AG, Germany. www.testo.de

SeTAR SOP # *The Heterogeneous Stove Testing Procedure for Thermal Performance and Trace Gas Emissions*, SeTAR Internal Report No. 01-10, University of Johannesburg, 2010.

TESTO® Error Sheet No. 330, Service office Report for August 2006, Testo AG, Germany.

TESTO® *Field guide: Control and adjustment of portable flue gas analysers*, Testo AG, Germany. www.testo350.com/pdfs/Inst_Man_350_Cal.pdf

8 DOCUMENT CHANGES

16 August, 2010: added signatures to the title page and adjusted page numbering.